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SECTION 4

PROPERTIES OF MATERIALS

Philip Mason Opsal

Wood Scientist, Wood Science LLC, Tucson, AZ

Grateful acknowledgement is also given to former contributors:

Donald J. Barta

Phelps Dodge Company

T. W. Dakin

Westinghouse Research Laboratories

Charles A Harper

Technology Seminars, Inc.

Duane E. Lyon

Professor, Mississippi State University

Charles B. Rawlins

Alcoa Conductor Products

James Stubbins

Professor, University of Illinois

John Tanaka

Professor, University of Connecticut

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4.1 CONDUCTOR MATERIALS

4.1.1 General Properties

Conducting Materials. A *conductor of electricity* is any substance or material which will afford continuous passage to an electric current when subjected to a difference of electric potential. The greater the density of current for a given potential difference, the more efficient the conductor is said to be. Virtually, all substances in solid or liquid state possess the property of electric conductivity in some degree, but certain substances are relatively efficient conductors, while others are almost totally devoid of this property. The metals, for example, are the best conductors, while many other substances, such as metal oxides and salts, minerals, and fibrous materials, are relatively poor conductors, but their conductivity is beneficially affected by the absorption of moisture. Some of the less-efficient conducting materials such as carbon and certain metal alloys, as well as the efficient conductors such as copper and aluminum, have very useful applications in the electrical arts.

Certain other substances possess so little conductivity that they are classed as nonconductors, a better term being insulators or dielectrics. In general, all materials which are used commercially for conducting electricity for any purpose are classed as conductors.

Definition of Conductor. A *conductor* is a body so constructed from conducting material that it may be used as a carrier of electric current. In ordinary engineering usage, a conductor is a material of relatively high conductivity.

Types of Conductors. In general, a conductor consists of a solid wire or a multiplicity of wires stranded together, made of a conducting material and used either bare or insulated. Only bare conductors are considered in this subsection. Usually the conductor is made of copper or aluminum, but for applications requiring higher strength, such as overhead transmission lines, bronze, steel, and various composite constructions are used. For conductors having very low conductivity and used as resistor materials, a group of special alloys is available.

Definition of Circuit. An *electric circuit* is the path of an electric current, or more specifically, it is a conducting part or a system of parts through which an electric current is intended to flow. Electric

circuits in general possess four fundamental electrical properties, consisting of resistance, inductance, capacitance, and leakage conductance. That portion of a circuit which is represented by its conductors will also possess these four properties, but only two of them are related to the properties of the conductor considered by itself. Capacitance and leakage conductance depend in part on the external dimensions of the conductors and their distances from one another and from other conducting bodies, and in part on the dielectric properties of the materials employed for insulating purposes. The inductance is a function of the magnetic field established by the current in a conductor, but this field as a whole is divisible into two parts, one being wholly external to the conductor and the other being wholly within the conductor; only the latter portion can be regarded as corresponding to the magnetic properties of the conductor material. The resistance is strictly a property of the conductor itself. Both the resistance and the internal inductance of conductors change in effective values when the current changes with great rapidity as in the case of high-frequency alternating currents; this is termed the *skin effect*.

In certain cases, conductors are subjected to various mechanical stresses. Consequently, their weight, tensile strength, and elastic properties require consideration in all applications of this character. Conductor materials as a class are affected by changes in temperature and by the conditions of mechanical stress to which they are subjected in service. They are also affected by the nature of the mechanical working and the heat treatment which they receive in the course of manufacture or fabrication into finished products.

4.1.2 Metal Properties

Specific Gravity and Density. Specific gravity is the ratio of mass of any material to that of the same volume of water at 4°C. Density is the unit weight of material expressed as pounds per cubic inch, grams per cubic centimeter, etc., at some reference temperature, usually 20°C. For all practical purposes, the numerical values of specific gravity and density are the same, expressed in g/cm³.

Density and Weight of Copper. Pure copper, rolled, forged, or drawn and then annealed, has a density of 8.89 g/cm³ at 20°C or 8.90 g/cm³ at 0°C. Samples of high-conductivity copper usually will vary from 8.87 to 8.91 and occasionally from 8.83 to 8.94. Variations in density may be caused by microscopic flaws or seams or the presence of scale or some other defect; the presence of 0.03% oxygen will cause a reduction of about 0.01 in density. Hard-drawn copper has about 0.02% less density than annealed copper, on average, but for practical purposes the difference is negligible.

The international standard of density, 8.89 at 20°C, corresponds to a weight of 0.32117 lb/in³ or 3.0270×10^{-6} lb/(cmil)(ft) or 15.982×10^{-3} lb/(cmil)(mile). Multiplying either of the last two figures by the square of the diameter of the wire in mils will produce the total weight of wire in pounds per foot or per mile, respectively.

Copper Alloys. Density and weight of copper alloys vary with the composition. For hard-drawn wire covered by ASTM Specification B105, the density of alloys 85 to 20 is 8.89 g/cm³ (0.32117 lb/in³) at 20°C; alloy 15 is 8.54 (0.30853); alloys 13 and 8.5 is 8.78 (0.31720).

Copper-Clad Steel. Density and weight of copper-clad steel wire is a mean between the density of copper and the density of steel, which can be calculated readily when the relative volumes or cross sections of copper and steel are known. For practical purposes, a value of 8.15 g/cm³ (0.29444 lb/in³) at 20°C is used.

Aluminum Wire. Density and weight of aluminum wire (commercially hard-drawn) is 2.705 g/cm³ (0.0975 lb/in³) at 20°C. The density of electrolytically refined aluminum (99.97% Al) and of hard-drawn wire of the same purity is 2.698 at 20°C. With less pure material there is an appreciable decrease in density on cold working. Annealed metal having a density of 2.702 will have a density of about 2.700 when in the hard-drawn or fully cold-worked conditions (see *NBS Circ.* 346, pp. 68 and 69).

Aluminum-Clad Wire. Density and weight of aluminum-clad wire is a mean between the density of aluminum and the density of steel, which can be calculated readily when the relative volumes or cross sections of aluminum and steel are known. For practical purposes, a value of 6.59 g/cm³ (0.23808 lb/in³) at 20°C is used.

Aluminum Alloys. Density and weight of aluminum alloys vary with type and composition. For hard-drawn aluminum alloy wire 5005-H19 and 6201-T81, a value of 2.703 g/cm³ (0.09765 lb/in³) at 20°C is used.

Pure Iron and Galvanized Steel Wire. Density and weight of pure iron is 7.90 g/cm^3 [$2.690 \times 10^{-6} \text{ lb/(cmil)(ft)}$] at 20°C . Density and weight of galvanized steel wire (EBB, BB, HTL-85, HTL-135, and HTL-195) with Class A weight of zinc coating are 7.83 g/cm^3 (0.283 lb/in^3) at 20°C , with Class B are 7.80 g/cm^3 (0.282 lb/in^3), and with Class C are 7.78 g/cm^3 (0.281 lb/in^3).

Percent Conductivity. It is very common to rate the conductivity of a conductor in terms of its percentage ratio to the conductivity of chemically pure metal of the same kind as the conductor is primarily constituted or in ratio to the conductivity of the international copper standard. Both forms of the conductivity ratio are useful for various purposes. This ratio also can be expressed in two different terms, one where the conductor cross sections are equal and therefore termed the *volume-conductivity ratio* and the other where the conductor masses are equal and therefore termed the *mass-conductivity ratio*.

International Annealed Copper Standard. The International Annealed Copper Standard (IACS) is the internationally accepted value for the resistivity of annealed copper of 100% conductivity. This standard is expressed in terms of mass resistivity as $0.5328 \Omega \cdot \text{g/m}^2$, or the resistance of a uniform round wire 1 m long weighing 1 g at the standard temperature of 20°C . Equivalent expressions of the annealed copper standard in various units of mass resistivity and volume resistivity are as follows:

0.15328	$\Omega \cdot \text{g/m}^2$
875.20	$\Omega \cdot \text{lb/mi}^2$
1.7241	$\mu\Omega \cdot \text{cm}$
0.67879	$\mu\Omega \cdot \text{in at } 20^\circ\text{C}$
10.371	$\Omega \cdot \text{cmil/ft}$
0.017241	$\Omega \cdot \text{mm}^2/\text{m}$

The preceding values are the equivalent of $1/58 \Omega \cdot \text{mm}^2/\text{m}$, so the volume conductivity can be expressed as $58 \text{ S} \cdot \text{mm}^2/\text{m}$ at 20°C .

Conductivity of Conductor Materials. Conductivity of conductor materials varies with chemical composition and processing.

Electrical Resistivity. *Electrical resistivity* is a measure of the resistance of a unit quantity of a given material. It may be expressed in terms of either mass or volume; mathematically,

Mass resistivity:
$$\delta = \frac{Rm}{l^2} \quad (4-1)$$

Volume resistivity:
$$\rho = \frac{RA}{l} \quad (4-2)$$

where R is resistance, m is mass, A is cross-sectional area, and l is length.

Electrical resistivity of conductor materials varies with chemical composition and processing.

Effects of Temperature Changes. Within the temperature ranges of ordinary service there is no appreciable change in the properties of conductor materials, except in electrical resistance and physical dimensions. The change in resistance with change in temperature is sufficient to require consideration in many engineering calculations. The change in physical dimensions with change in temperature is also important in certain cases, such as in overhead spans and in large units of apparatus or equipment.

Temperature Coefficient of Resistance. Over moderate ranges of temperature, such as 100°C , the change of resistance is usually proportional to the change of temperature. Resistivity is always expressed at a standard temperature, usually 20°C (68°F). In general, if R_{t_1} is the resistance at a temperature t_1

and α_{t_1} is the temperature coefficient at that temperature, the resistance at some other temperature t_2 is expressed by the formula

$$R_{t_2} = R_{t_1} [1 + \alpha_{t_1} (t_2 - t_1)] \quad (4-3)$$

Over wide ranges of temperature, the linear relationship of this formula is usually not applicable, and the formula then becomes a series involving higher powers of t , which is unwieldy for ordinary use.

When the temperature of reference t_1 is changed to some other value, the coefficient also changes. Upon assuming the general linear relationship between resistance and temperature previously mentioned, the new coefficient at any temperature t within the linear range is expressed

$$\alpha_t = \frac{1}{(1/\alpha_{t_1}) + (t - t_1)} \quad (4-4)$$

The reciprocal of α is termed the *inferred absolute zero of temperature*. Equation (4-3) takes no account of the change in dimensions with change in temperature and therefore applies to the case of conductors of constant mass, usually met in engineering work.

The *coefficient for copper of less than standard (or 100%) conductivity* is proportional to the actual conductivity, expressed as a decimal percentage. Thus, if n is the percentage conductivity ($95\% = 0.95$), the temperature coefficient will be $\alpha'_t = n\alpha_t$, where α_t is the coefficient of the annealed copper standard.

The coefficients are computed from the formula

$$\alpha_t = \frac{1}{[1/n(0.00393)] + (t_1 - 20)} \quad (4-5)$$

Copper Alloys and Copper-Clad Steel Wire. Temperature-resistance coefficients for copper alloys usually can be approximated by multiplying the corresponding coefficient for copper (100% IACS) by the alloy conductivity expressed as a decimal. For some complex alloys, however, this relation does not hold even approximately, and suitable values should be obtained from the supplier. The temperature-resistance coefficient for copper-clad steel wire is $0.00378/^{\circ}\text{C}$ at 20°C .

Aluminum-Alloy Wires and Aluminum-Clad Wire. Temperature-resistance coefficients for aluminum-alloy wires are for 5005 H19, $0.00353/^{\circ}\text{C}$, and for 6201-T81, $0.00347/^{\circ}\text{C}$ at 20°C . Temperature-resistance coefficient for aluminum-clad wire is $0.0036/^{\circ}\text{C}$ at 20°C .

Typical Composite Conductors. Temperature-resistance coefficients for typical composite conductors are as follows:

Type	Approximate temperature coefficient per $^{\circ}\text{C}$ at 20°C
Copper-copper-clad steel	0.00381
ACSR (aluminum-steel)	0.00403
Aluminum-aluminum alloy	0.00394
Aluminum-aluminum-clad steel	0.00396

Reduction of Observations to Standard Temperature. A table of convenient corrections and factors for reducing resistivity and resistance to standard temperature, 20°C , will be found in Copper Wire Tables, *NBS Handbook 100*.

Resistivity-Temperature Constant. The *change of resistivity per degree* may be readily calculated, taking account of the expansion of the metal with rise of temperature. The proportional relation between temperature coefficient and conductivity may be put in the following convenient form for reducing *resistivity* from one temperature to another. *The change of resistivity of copper per degree Celsius is a constant, independent of the temperature of reference and of the sample of copper. This "resistivity-temperature constant" may be taken, for general purposes, as 0.00060Ω (meter, gram), or $0.0068 \mu\Omega \cdot \text{cm}$.*

Details of the calculation of the resistivity-temperature constant will be found in Copper Wire Tables, *NBS Handbook* 100; also see this reference for expressions for the temperature coefficients of resistivity and their derivation.

Temperature Coefficient of Expansion. *Temperature coefficient of expansion* (linear) of pure metals over a range of several hundred degrees is not a linear function of the temperature but is well expressed by a quadratic equation

$$\frac{L_{t_2}}{L_{t_1}} = 1 + [\alpha(t_2 - t_1) + \beta(t_2 - t_1)^2] \quad (4-6)$$

Over the temperature ranges for ordinary engineering work (usually 0 to 100°C), the coefficient can be taken as a constant (assumed linear relationship) and a simplified formula employed

$$L_{t_2} = L_{t_1}[1 + \alpha_{t_1}(t_2 - t_1)] \quad (4-7)$$

Changes in linear dimensions, superficial area, and volume take place in most materials with changes in temperature. In the case of linear conductors, only the change in length is ordinarily important.

The coefficient for changes in superficial area is approximately twice the coefficient of linear expansion for relatively small changes in temperature. Similarly, the volume coefficient is 3 times the linear coefficient, with similar limitations.

Specific Heat. Specific heat of electrolytic tough pitch copper is 0.092 cal/(g)(°C) at 20°C (see *NBS Circ.* 73). Specific heat of aluminum is 0.226 cal/(g)(°C) at room temperature (see *NBS Circ.* C447, Mechanical Properties of Metals and Alloys). Specific heat of iron (wrought) or very soft steel from 0 to 100°C is 0.114 cal/(g)(°C); the true specific heat of iron at 0°C is 0.1075 cal/(g)(°C) (see *International Critical Tables*, vol. II, p. 518; also ASM, *Metals Handbook*).

Thermal Conductivity of Electrolytic Tough Pitch Copper. Thermal conductivity of electrolytic tough pitch copper at 20°C is 0.934 cal/(cm²)(cm)(s)(°C), adjusted to correspond to an electrical conductivity of 101% (see *NBS Circ.* 73).

Thermal-Electrical Conductivity Relation of Copper. The Wiedemann-Franz-Lorenz law, which states that the ratio of the thermal and electrical conductivities at a given temperature is independent of the nature of the conductor, holds closely for copper. The ratio $K/\lambda T$ (where K = thermal conductivity, λ = electrical conductivity, T = absolute temperature) for copper is 5.45 at 20°C.

Thermal Conductivity. *Copper Alloys.*

ASTM alloy (Spec. B105)	Thermal conductivity (volumetric) at 20°C	
	Btu per sq ft per ft per h per °F	Cal per sq cm per cm per sec per °C
8.5	31	0.13
15	50	0.21
30	84	0.35
55	135	0.56
80	199	0.82
85	208	0.86

Aluminum. The determination made by the Bureau of Standards at 50°C for aluminum of 99.66% purity is 0.52 cal/(cm²)(cm)(s)(°C) (*Circ.* 346; also see *Smithsonian Physical Tables and International Critical Tables*).

Iron. Thermal conductivity of iron (mean) from 0 to 100°C is 0.143 cal/(cm²)(cm)(s)(°C); with increase of carbon and manganese content, it tends to decrease and may reach a figure of approximately

0.095 with about 1% carbon, or only about half of that figure if the steel is hardened by water quenching (see *International Critical Tables*, vol. II, p. 518).

Copper. Copper is a highly malleable and ductile metal of reddish color. It can be cast, forged, rolled, drawn, and machined. Mechanical working hardens it, but annealing will restore it to the soft state. The density varies slightly with the physical state, 8.9 being an average value. It melts at 1083°C (1981°F) and in the molten state has a sea-green color. When heated to a very high temperature, it vaporizes and burns with a characteristic green flame. Copper readily alloys with many other metals. In ordinary atmospheres it is not subject to appreciable corrosion. Its electrical conductivity is very sensitive to the presence of slight impurities in the metal.

Copper, when exposed to ordinary atmospheres, becomes oxidized, turning to a black color, but the oxide coating is protective, and the oxidizing process is not progressive. When exposed to moist air containing carbon dioxide, it becomes coated with green basic carbonate, which is also protective. At temperatures above 180°C it oxidizes in dry air. In the presence of ammonia it is readily oxidized in air, and it is also affected by sulfur dioxide. Copper is not readily attacked at high temperatures below the melting point by hydrogen, nitrogen, carbon monoxide, carbon dioxide, or steam. Molten copper readily absorbs oxygen, hydrogen, carbon monoxide, and sulfur dioxide, but on cooling, the occluded gases are liberated to a great extent, tending to produce blowholes or porous castings. Copper in the presence of air does not dissolve in dilute hydrochloric or sulfuric acid but is readily attacked by dilute nitric acid. It is also corroded slowly by saline solutions and sea water.

Commercial grades of copper in the United States are electrolytic, oxygen-free, Lake, fire-refined, and casting. *Electrolytic copper* is that which has been electrolytically refined from blister, converter, black, or Lake copper. *Oxygen-free copper* is produced by special manufacturing processes which prevent the absorption of oxygen during the melting and casting operations or by removing the oxygen by reducing agents. It is used for conductors subjected to reducing gases at elevated temperature, where reaction with the included oxygen would lead to the development of cracks in the metal. *Lake copper* is electrolytically or fire-refined from Lake Superior native copper ores and is of two grades, low resistance and high resistance. *Fire-refined copper* is a lower-purity grade intended for alloying or for fabrication into products for mechanical purposes; it is not intended for electrical purposes. *Casting copper* is the grade of lowest purity and may consist of furnace-refined copper, rejected metal not up to grade, or melted scrap; it is exclusively a foundry copper.

Hardening and Heat-Treatment of Copper. There are but two well-recognized methods for hardening copper, one is by mechanically working it, and the other is by the addition of an alloying element. The properties of copper are not affected by a rapid cooling after annealing or rolling, as are those of steel and certain copper alloys.

Annealing of Copper. Cold-worked copper is softened by annealing, with decrease of tensile strength and increase of ductility. In the case of pure copper hardened by cold reduction of area to one-third of its initial area, this softening takes place with maximum rapidity between 200 and 325°C. However, this temperature range is affected in general by the extent of previous cold reduction and the presence of impurities. The greater the previous cold reduction, the lower is the range of softening temperatures. The effect of iron, nickel, cobalt, silver, cadmium, tin, antimony, and tellurium is to lower the conductivity and raise the annealing range of pure copper in varying degrees.

Commercial grade	ASTM Designation	Copper content, minimum %
Electrolytic	B5	99.900
Oxygen-free electrolytic	B170	99.95
Lake, low resistance	B4	99.900
Lake, high resistance	B4	99.900
Fire-refined	B216	99.88
Casting	B119	98

Alloying of Copper. Elements that are soluble in moderate amounts in a solid solution of copper, such as manganese, nickel, zinc, tin, and aluminum, generally harden it and diminish its ductility but improve its rolling and working properties. Elements that are but slightly soluble, such as bismuth and lead, do not harden it but diminish both the ductility and the toughness and impair its hot-working properties. Small additions (up to 1.5%) of manganese, phosphorus, or tin increase the tensile strength and hardness of cold-rolled copper.

Brass is usually a binary alloy of copper and zinc, but brasses are seldom employed as electrical conductors, since they have relatively low conductivity through comparatively high tensile strength. In general, brass is not suitable for use when exposed to the weather, owing to the difficulty from stress-corrosion cracking; the higher the zinc content, the more pronounced this becomes.

Bronze in its simplest form is a binary alloy of copper and tin in which the latter element is the hardening and strengthening agent. This material is rather old in the arts and has been used to some extent for electrical conductors for past many years, especially abroad. Modern bronzes are frequently ternary alloys, containing as the third constituent such elements as phosphorus, silicon, manganese, zinc, aluminum, or cadmium; in such cases, the third element is usually given in the name of the alloy, as in phosphor bronze or silicon bronze. Certain bronzes are quaternary alloys, or contain two other elements in addition to copper and tin.

In bronzes for use as electrical conductors, the content of tin and other metals is usually less than in bronzes for structural or mechanical applications, where physical properties and resistance to corrosion are the governing considerations. High resistance to atmospheric corrosion is always an important consideration in selecting bronze conductors for overhead service.

Commercial Grades of Bronze. Various bronzes have been developed for use as conductors, and these are now covered by ASTM Specification B105. They all have been designed to provide conductors having high resistance to corrosion and tensile strengths greater than hard-drawn copper conductors. The standard specification covers 10 grades of bronze, designated by numbers according to their conductivities.

Copper-Beryllium Alloy. *Copper-beryllium alloy* containing 0.4% of beryllium may have an electrical conductivity of 48% and a tensile strength (in 0.128-in wire) of 86,000 lb/in². A content of 0.9% of beryllium may give a conductivity of 28% and a tensile strength of 122,000 lb/in². The effect of this element in strengthening copper is about 10 times as great as that of tin.

Copper-Clad Steel Wire. *Copper-clad steel wire* has been manufactured by a number of different methods. The general object sought in the manufacture of such wires is the combination of the high conductivity of copper with the high strength and toughness of iron or steel. The principal manufacturing processes now in commercial use are (a) coating a steel billet with a special flux, placing it in a vertical mold closed at the bottom, heating the billet and mold to yellow heat, and then casting molten copper around the billet, after which it is hot-rolled to rods and cold-drawn to wire, and (b) electroplating a dense coating of copper on a steel rod and then cold drawing to wire.

Aluminum. *Aluminum* is a ductile metal, silver-white in color, which can be readily worked by rolling, drawing, spinning, extruding, and forging. Its specific gravity is 2.703. Pure aluminum melts at 660°C (1220°F). Aluminum has relatively high thermal and electrical conductivities. The metal is always covered with a thin, invisible film of oxide which is impermeable and protective in character. Aluminum, therefore, shows stability and long life under ordinary atmospheric exposure.

Exposure to atmospheres high in hydrogen sulfide or sulfur dioxide does not cause severe attack of aluminum at ordinary temperatures, and for this reason, aluminum or its alloys can be used in atmospheres which would be rapidly corrosive to many other metals.

Aluminum parts should, as a rule, not be exposed to salt solutions while in electrical contact with copper, brass, nickel, tin, or steel parts, since galvanic attack of the aluminum is likely to occur. Contact with cadmium in such solutions results in no appreciable acceleration in attack on the aluminum, while

contact with zinc (or zinc-coated steel as long as the coating is intact) is generally beneficial, since the zinc is attacked selectively and it cathodically protects adjacent areas of the aluminum.

Most organic acids and their water solutions have little or no effect on aluminum at room temperature, although oxalic acid is an exception and is corrosive. Concentrated nitric acid (about 80% by weight) and fuming sulfuric acid can be handled in aluminum containers. However, more dilute solutions of these acids are more active. All but the most dilute (less than 0.1%) solutions of hydrochloric and hydrofluoric acids have a rapid etching action on aluminum.

Solutions of the strong alkalis, potassium, or sodium hydroxides dissolve aluminum rapidly. However, ammonium hydroxide and many of the strong organic bases have little action on aluminum and are successfully used in contact with it (see *NBS Circ.* 346).

Aluminum in the presence of water and limited air or oxygen rapidly converts into aluminum hydroxide, a whitish powder.

Commercial grades of aluminum in the United States are designated by their purity, such as 99.99, 99.6, 99.2, 99.0%. Electrical conductor alloy aluminum 1350, having a purity of approximately 99.5% and a minimum conductivity of 61.0% IACS, is used for conductor purposes. Specified physical properties are obtained by closely controlling the kind and amount of certain impurities.

Annealing of Aluminum. Cold-worked aluminum is softened by annealing, with decrease of tensile strength and increase of ductility. The annealing temperature range is affected in general by the extent of previous cold reduction and the presence of impurities. The greater the previous cold reduction, the lower is the range of softening temperatures.

Alloying of Aluminum. Aluminum can be alloyed with a variety of other elements, with a consequent increase in strength and hardness. With certain alloys, the strength can be further increased by suitable heat treatment. The alloying elements most generally used are copper, silicon, manganese, magnesium, chromium, and zinc. Some of the aluminum alloys, particularly those containing one or more of the following elements—copper, magnesium, silicon, and zinc—in various combinations, are susceptible to heat treatment.

Pure aluminum, even in the hard-worked condition, is a relatively weak metal for construction purposes. Strengthening for castings is obtained by alloying elements. The alloys most suitable for cold rolling seldom contain less than 90% to 95% aluminum. By alloying, working, and heat treatment, it is possible to produce tensile strengths ranging from 8500 lb/in² for pure annealed aluminum up to 82,000 lb/in² for special wrought heat-treated alloy, with densities ranging from 2.65 to 3.00.

Electrical conductor alloys of aluminum are principally alloys 5005 and 6201 covered by ASTM Specifications B396 and B398.

Aluminum-clad steel wires have a relatively heavy layer of aluminum surrounding and bonded to the high-strength steel core. The aluminum layer can be formed by compacting and sintering a layer of aluminum powder over a steel rod, by electroplating a dense coating of aluminum on a steel rod, or by extruding a coating of aluminum on a steel rod and then cold drawing to wire.

Silicon. Silicon is a light metal having a specific gravity of approximately 2.34. There is lack of accurate data on the pure metal because its mechanical brittleness bars it from most industrial uses. However, it is very resistant to atmospheric corrosion and to attack by many chemical reagents. Silicon is of fundamental importance in the steel industry, but for this purpose it is obtained in the form of ferrosilicon, which is a coarse granulated or broken product. It is very useful as an alloying element in steel for electrical sheets and substantially increases the electrical resistivity, and thereby reduces the core losses. Silicon is peculiar among metals in the respect that its temperature coefficient of resistance may change sign in some temperature ranges, the exact behavior varying with the impurities.

Beryllium. Beryllium is a light metal having a specific gravity of approximately 1.84, or nearly the same as magnesium. It is normally hard and brittle and difficult to fabricate. Copper is materially

strengthened by the addition of small amounts of beryllium, without very serious loss of electrical conductivity. The principal use for this metal appears to be as an alloying element with other metals such as aluminum and copper. Beryllium is also toxic. Reference should be made to Material Safety Data Sheets for precautions in handling.

Sodium. *Sodium* is a soft, bright, silvery metal obtained commercially by the electrolysis of absolutely dry fused sodium chloride. It is the most abundant of the alkali group of metals, is extremely reactive, and is never found free in nature. It oxidizes readily and rapidly in air. In the presence of water (it is so light that it floats) it may ignite spontaneously, decomposing the water with evolution of hydrogen and formation of sodium hydroxide. This can be explosive. Sodium should be handled with respect, since it can be dangerous when handled improperly. It melts at 97.8°C, below the boiling point of water and in the same range as many fuse metal alloys. Sodium is approximately one-tenth as heavy as copper and has roughly three-eighths the conductivity; hence 1 lb of sodium is about equal electrically to 3½ lb of copper.

4.1.3 Conductor Properties

Definitions of Electrical Conductors

Wire. A rod or filament of drawn or rolled metal whose length is great in comparison with the major axis of its cross section. The definition restricts the term to what would ordinarily be understood by the term *solid wire*. In the definition, the word *slender* is used in the sense that the length is great in comparison with the diameter. If a wire is covered with insulation, it is properly called an *insulated wire*, while primarily the term *wire* refers to the metal; nevertheless, when the context shows that the wire is insulated, the term *wire* will be understood to include the insulation.

Conductor. A wire or combination of wires not insulated from one another, suitable for carrying an electric current. The term *conductor* is not to include a combination of conductors insulated from one another, which would be suitable for carrying several different electric currents. Rolled conductors (such as bus bars) are, of course, conductors but are not considered under the terminology here given.

Stranded Conductor. A conductor composed of a group of wires, usually twisted, or any combination of groups of wires. The wires in a stranded conductor are usually twisted or braided together.

Cable. A stranded conductor (single-conductor cable) or a combination of conductors insulated from one another (multiple-conductor cable). The component conductors of the second kind of cable may be either solid or stranded, and this kind of cable may or may not have a common insulating covering. The first kind of cable is a single conductor, while the second kind is a group of several conductors. The term *cable* is applied by some manufacturers to a solid wire heavily insulated and lead covered; this usage arises from the manner of the insulation, but such a conductor is not included under this definition of *cable*. The term *cable* is a general one, and in practice, it is usually applied only to the larger sizes. A small cable is called a *stranded wire* or a *cord*, both of which are defined below. Cables may be bare or insulated, and the latter may be armored with lead or with steel wires or bands.

Strand. One of the wires of any stranded conductor.

Stranded Wire. A group of small wires used as a single wire. A *wire* has been defined as a slender rod or filament of drawn metal. If such a filament is subdivided into several smaller filaments or strands and is used as a single wire, it is called *stranded wire*. There is no sharp dividing line of size between a stranded wire and a cable. If used as a wire, for example, in winding inductance coils or magnets, it is called a *stranded wire* and not a cable. If it is substantially insulated, it is called a *cord*, defined below.

Cord. A small cable, very flexible and substantially insulated to withstand wear. There is no sharp dividing line in respect to size between a cord and a cable, and likewise no sharp dividing line

in respect to the character of insulation between a cord and a stranded wire. Usually the insulation of a cord contains rubber.

Concentric Strand. A strand composed of a central core surrounded by one or more layers of helically laid wires or groups of wires.

Concentric-Lay Conductor. Conductor constructed with a central core surrounded by one or more layers of helically laid wires.

Rope-Lay Conductor. Conductor constructed of a bunch-stranded or a concentric-stranded member or members, as a central core, around which are laid one or more helical layers of such members.

N-Conductor Cable. A combination of N conductors insulated from one another. It is not intended that the name as given here actually be used. One would instead speak of a "3-conductor cable," a "12-conductor cable," etc. In referring to the general case, one may speak of a "multiple-conductor cable."

N-Conductor Concentric Cable. A cable composed of an insulated central conducting core with $N-1$ tubular-stranded conductors laid over it concentrically and separated by layers of insulation. This kind of cable usually has only two or three conductors. Such cables are used in carrying alternating currents. The remark on the expression " N conductor" given for the preceding definition applies here also. (Additional definitions can be found in ASTM B354.)

Wire Sizes. Wire sizes have been for many years indicated in commercial practice almost entirely by gage numbers, especially in America and England. This practice is accompanied by some confusion because numerous gages are in common use. The most commonly used gage for electrical wires, in America, is the *American wire gage*. The most commonly used gage for steel wires is the *Birmingham wire gage*.

There is no legal standard wire gage in this country, although a gage for sheets was adopted by Congress in 1893. In England, there is a legal standard known as the *Standard wire gage*. In Germany, France, Austria, Italy, and other continental countries, practically no wire gage is used, but wire sizes are specified directly in millimeters. This system is sometimes called the *millimeter wire gage*. The wire sizes used in France, however, are based to some extent on the old Paris gage (*jauge de Paris de 1857*) (for a history of wire gages, see *NBS Handbook 100*, Copper Wire Tables; also see *Circ. 67*, Wire Gages, 1918).

There is a tendency to *abandon gage numbers* entirely and specify wire sizes by the *diameter in mils* (thousandths of an inch). This practice holds particularly in writing specifications and has the great advantages of being both simple and explicit. A number of wire manufacturers also encourage this practice, and it was definitely adopted by the U.S. Navy Department in 1911.

Mil is a term universally employed in this country to measure wire diameters and is a unit of length equal to one-thousandth of an inch. *Circular mil* is a term universally used to define cross-sectional areas, being a unit of area equal to the area of a circle 1 mil in diameter. Such a circle, however, has an area of 0.7854 (or $\pi/4$) mil². Thus a wire 10 mils in diameter has a cross-sectional area of 100 cmils or 78.54 mils². Hence, a cmil equals 0.7854 mil².

American wire gage, also known as the *Brown & Sharpe gage*, was devised in 1857 by J. R. Brown. It is usually abbreviated AWG. This gage has the property, in common with a number of other gages, that its sizes represent approximately the successive steps in the process of wire drawing. Also, like many other gages, its numbers are retrogressive, a larger number denoting a smaller wire, corresponding to the operations of drawing. These gage numbers are not arbitrarily chosen, as in many gages, but follow the mathematical law upon which the gage is founded.

Basis of the AWG is a simple mathematical law. The gage is formed by the specification of two diameters and the law that a given number of intermediate diameters are formed by geometric progression. Thus, the diameter of No. 0000 is defined as 0.4600 in and of No. 36 as 0.0050 in. There are 38 sizes between these two; hence the ratio of any diameter to the diameter of the next greater number is given by this expression

$$\sqrt[39]{\frac{0.4600}{0.0050}} = \sqrt[39]{92} = 1.122\ 932\ 2 \quad (4-8)$$

The square of this ratio = 1.2610. The sixth power of the ratio, that is, the ratio of any diameter to the diameter of the sixth greater number, = 2.0050. The fact that this ratio is so nearly 2 is the basis of numerous useful relations or shortcuts in wire computations.

There are a number of approximate rules applicable to the AWG which are useful to remember:

1. An increase of three gage numbers (e.g., from No. 10 to 7) doubles the area and weight and consequently halves the dc resistance.
2. An increase of six gage numbers (e.g., from No. 10 to 4) doubles the diameter.
3. An increase of 10 gage numbers (e.g., from No. 10 to 1/0) multiplies the area and weight by 10 and divides the resistance by 10.
4. A No. 10 wire has a diameter of about 0.10 in, an area of about 10,000 cmils, and (for standard annealed copper at 20°C) a resistance of approximately 1.0 Ω /1000 ft.
5. The weight of No. 2 copper wire is very close to 200 lb/1000 ft (90 kg/304.8 m).

Steel wire gage, also known originally as the *Washburn & Moen gage* and later as the *American Steel & Wire Co.'s gage*, was established by Ichabod Washburn in 1830. This gage, with a number of its sizes rounded off to thousandths of an inch, is also known as the *Roebbling gage*. It is used exclusively for steel wire and is frequently employed in wire mills.

Birmingham wire gage, also known as *Stubs' wire gage* and *Stubs' iron wire gage*, is said to have been established early in the eighteenth century in England, where it was long in use. This gage was used to designate the Stubs soft-wire sizes and should not be confused with Stubs' steel-wire gage. The numbers of the Birmingham gage were based on the reductions of size made in practice by drawing wire from rolled rod. Thus, a wire rod was called "No. 0," "first drawing No. 1," and so on. The gradations of size in this gage are not regular, as will appear from its graph. This gage is generally in commercial use in the United States for iron and steel wires.

Standard wire gage, which more properly should be designated (*British*) *Standard wire gage*, is the legal standard of Great Britain for all wires adopted in 1883. It is also known as the *New British Standard gage*, the *English legal standard gage*, and the *Imperial wire gage*. It was constructed by so modifying the Birmingham gage that the differences between consecutive sizes become more regular. This gage is largely used in England but never has been used extensively in America.

Old English wire gage, also known as the *London wire gage*, differs very little from the Birmingham gage. Formerly it was used to some extent for brass and copper wires but is now nearly obsolete.

Millimeter wire gage, also known as the *metric wire gage*, is based on giving progressive numbers to the progressive sizes, calling 0.1 mm diameter "No. 1," 0.2 mm "No. 2," etc.

Conductor-Size Designation. America uses, for sizes up to 4/0, mil, decimals of an inch, or AWG numbers for solid conductors and AWG numbers or circular mils for stranded conductors; for sizes larger than 4/0, circular mils are used throughout. Other countries ordinarily use square millimeter area.

Conductor-size conversion can be accomplished from the following relation:

$$\text{cmils} = \text{in}^2 \times 1,273,200 = \text{mm}^2 \times 1973.5 \quad (4-9)$$

Measurement of wire diameters may be accomplished in many ways but most commonly by means of a micrometer caliper. Stranded cables are usually measured by means of a circumference tape calibrated directly in diameter readings.

Stranded Conductors. Stranded conductors are used generally because of their increased flexibility and consequent ease in handling. The greater the number of wires in any given cross section, the greater will be the flexibility of the finished conductor. Most conductors above 4/0 AWG in size are stranded. Generally, in a given concentric-lay stranded conductor, all wires are of the same size and the same material, although special conductors are available embodying wires of different sizes and materials. The former will be found in some insulated cables and the latter in overhead stranded conductors combining high-conductivity and high-strength wires.

The flexibility of any given size of strand obviously increases as the total number of wires increases. It is a common practice to increase the total number of wires as the strand diameter increases in order to provide reasonable flexibility in handling. So-called flexible concentric strands for use in insulated cables have about one to two more layers of wires than the standard type of strand for ordinary use.

Number of Wires in Standard Conductors. Each successive layer in a concentrically stranded conductor contains six more wires than the preceding one. The total number of wires in a conductor is For 1-wire core constructions (1, 7, 19, etc.),

$$N = 3n(n + 1) + 1 \quad (4-10)$$

For 3-wire core constructions (3, 12, etc.),

$$N = 3n(n + 2) + 3 \quad (4-11)$$

where n is number of layers over core, which is not counted as a layer.

Wire size in stranded conductors is

$$d = \sqrt{\frac{A}{N}} \quad (4-12)$$

where A is total conductor area in circular mils, and N is total number of wires.

Copper cables are manufactured usually to certain cross-sectional sizes specified in total circular mils or by gage numbers in AWG. This necessarily requires individual wires drawn to certain prescribed diameters, which are different as a rule from normal sizes in AWG (see Table 4-10).

Diameter of stranded conductors (circumscribing circle) is

$$D = d(2n + k) \quad (4-13)$$

where d is diameter of individual wire, n is number of layers over core, which is not counted as a layer, k is 1 for constructions having 1-wire core (1, 7, 19, etc.), and 2.155 for constructions having 3-wire core (3, 12, etc.).

For standard concentric-lay stranded conductors, the following rule gives a simple method of determining the outside diameter of a stranded conductor from the known diameter of a solid wire of the same cross-sectional area: *To obtain the diameter of concentric-lay stranded conductor, multiply the diameter of the solid wire of the same cross-sectional area by the appropriate factor as follows:*

Number of wires	Factor	Number of wires	Factor
3	1.244	91	1.153
7	1.134	127	1.154
12	1.199	169	1.154
19	1.147	217	1.154
37	1.151	271	1.154
61	1.152		

Area of stranded conductors is

$$A = Nd^2 \text{ cmils} = \frac{1}{4} \pi Nd^2 \times 10^{-6} \text{ in}^2 \quad (4-14)$$

where N is total number of wires, and d is individual wire diameter in mils.

Effects of Stranding. All wires in a stranded conductor except the core wire form continuous helices of slightly greater length than the axis or core. This causes a slight increase in weight and electrical resistance and slight decrease in tensile strength and sometimes affects the internal

inductance, as compared theoretically with a conductor of equal dimensions but composed of straight wires parallel with the axis.

Lay, or Pitch. The axial length of one complete turn, or helix, of a wire in a stranded conductor is sometimes termed the *lay*, or *pitch*. This is often expressed as the *pitch ratio*, which is the ratio of the length of the helix to its *pitch diameter* (diameter of the helix at the centerline of any individual wire or strand equals the outside diameter of the helix minus the thickness of one wire or strand). If there are several layers, the pitch expressed as an axial length may increase with each additional

layer, but when expressed as the ratio of axial length to pitch diameter of helix, it is usually the same for all layers, or nearly so. In commercial practice, the pitch is commonly expressed as the ratio of axial length to outside diameter of helix, but this is an arbitrary designation made for convenience of usage. The *pitch angle* is shown in Fig. 4-1, where ac represents the axis of the stranded conductor and l is the axial length of one complete turn or helix, ab is the length of any individual wire $l + \Delta l$ in one complete turn, and bc is equal to the circumference of a circle corresponding to the pitch

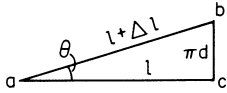


FIGURE 4-1 Pitch angle in concentric-lay cable.

diameter d of the helix. The angle bac , or θ , is the pitch angle, and the pitch ratio is expressed by $p = l/d$. There is no standard pitch ratio used by manufacturers generally, since it has been found desirable to vary this depending on the type of service for which the conductor is intended. Applicable lay lengths generally are included in industry specifications covering the various stranded conductors. For bare overhead conductors, a representative commercial value for pitch length is 13.5 times the outside diameter of each layer of strands.

Direction of Lay. The direction of lay is the lateral direction in which the individual wires of a cable run over the top of the cable as they recede from an observer looking along the axis. *Right-hand lay* recedes from the observer in clockwise rotation or like a right-hand screw thread; *left-hand lay* is the opposite. The outer layer of a cable is ordinarily applied with a right-hand lay for bare overhead conductors and left-hand lay for insulated conductors, although the opposite lay can be used if desired.

Increase in Weight Due to Stranding. Referring to Fig. 4-1, the increase in weight of the spiral members in a cable is proportional to the increase in length

$$\begin{aligned} \frac{l + \Delta l}{l} &= \sec \theta = \sqrt{1 + \tan^2 \theta} \\ &= \sqrt{1 + \frac{\pi^2}{p^2}} = 1 + \frac{1\pi^2}{2p^2} - \frac{1}{8} \left(\frac{\pi^2}{p^2} \right)^2 + \dots \end{aligned} \quad (4-15)$$

As a first approximation this ratio equals $1 + 0.5(\pi^2/p^2)$, and a pitch of 15.7 produces a ratio of 1.02. This correction factor should be computed separately for each layer if the pitch p varies from layer to layer.

Increase in Resistance Due to Stranding. If it were true that no current flows from wire to wire through their lineal contacts, the proportional increase in the total resistance would be the same as the proportional increase in total weight. If all the wires were in perfect and complete contact with each other, the total resistance would decrease in the same proportion that the total weight increases, owing to the slightly increased normal cross section of the cable as a whole. The contact resistances are normally sufficient to make the actual increase in total resistance nearly as much, proportionately, as the increase in total weight, and for practical purposes they are usually assumed to be the same.

Decrease in Strength Due to Stranding. When a concentric-lay cable is subjected to mechanical tension, the spiral members tend to tighten around those layers under them and thus produce internal compression, gripping the inner layers and the core. Consequently, the individual wires, taken as a whole, do not behave as they would if they were true linear conductors acting independently. Furthermore, the individual wires are never exactly alike in diameter or in strength or in elastic properties. For these reasons, there is ordinarily a loss of about 4% to 11% in total tensile efficiency, depending on the number of layers. This reduction tends to increase as the pitch ratio decreases. Actual tensile tests on cables furnish the most dependable data on their ultimate strength.

Tensile efficiency of a stranded conductor is the ratio of its breaking strength to the sum of the tensile strengths of all its individual wires. Concentric-lay cables of 12 to 16 pitch ratio have a normal tensile efficiency of approximately 90%; rope-lay cables, approximately 80%.

Preformed Cable. This type of cable is made by preforming each individual wire (except the core) into a spiral of such length and curvature that the wire will fit naturally into its normal position in the cable instead of being forced into that shape under the usual tension in the stranding machine. This method has the advantage in cable made of the stiffer grades of wire that the individual wires do not tend to spread or untwist if the strand is cut in two without first binding the ends on each side of the cut.

Weight. A uniform cylindrical conductor of diameter d , length l , and density δ has a total weight expressed by the formula

$$W = \delta l \frac{\pi d^2}{4} \quad (4-16)$$

The weight of any conductor is commonly expressed in pounds per unit of length, such as 1 ft, 1000 ft, or 1 mi. The weight of stranded conductors can be calculated using Eq. (4-16), but allowance must be made for increase in weight due to stranding. Rope-lay stranding has greater increase in weight because of the multiple stranding operations.

Breaking Strength. The maximum load that a conductor attains when tested in tension to rupture.

Total Elongation at Rupture. When a sample of any material is tested under tension until it ruptures, measurement is usually made of the total elongation in a certain initial test length. In certain kinds of testing, the initial test length has been standardized, but in every case, the total elongation at rupture should be referred to the initial test length of the sample on which it was measured. Such elongation is usually expressed in percentage of original unstressed length and is a general index of the ductility of the material. Elongation is determined on solid conductors or on individual wires before stranding; it is rarely determined on stranded conductors.

Elasticity. All materials are deformed in greater or lesser degree under application of mechanical stress. Such deformation may be either of two kinds, known, respectively, as *elastic deformation* and *permanent deformation*. When a material is subjected to stress and undergoes deformation but resumes its original shape and dimensions when the stress is removed, the deformation is said to be *elastic*. If the stress is so great that the material fails to resume its original dimensions when the stress is removed, the permanent change in dimensions is termed *permanent deformation* or *set*. In general, the stress at which appreciable permanent deformation begins is termed the *working elastic limit*. Below this limit of stress the behavior of the material is said to be *elastic*, and in general, the deformation is proportional to the stress.

Stress and Strain. The *stress* in a material under load, as in simple tension or compression, is defined as the total load divided by the area of cross section normal to the direction of the load, assuming the load to be uniformly distributed over this cross section. It is commonly expressed in pounds per square inch. The *strain* in a material under load is defined as the total deformation measured in

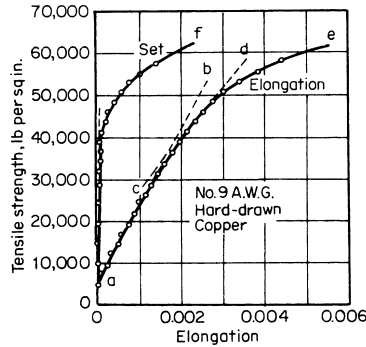


FIGURE 4-2 Stress-strain curves of No. 9 AWG hard-drawn copper wire. (Watertown Arsenal test).

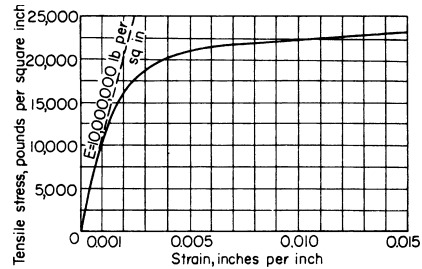


FIGURE 4-3 Typical stress-strain curve of hard drawn aluminum wire.

the direction of the stress, divided by the total unstressed length in which the measured deformation occurs, or the deformation per unit length. It is expressed as a decimal ratio or numeric.

In order to show the complete behavior of any given conductor under tension, it is customary to make a graph in terms of loading or stress as the ordinates and elongation or strain as the abscissas. Such graphs or curves are useful in determining the elastic limit and the yield point if the loading is carried to the point of rupture. Graphs showing the relationship between stress and strain in a material tested to failure are termed *load-deformation* or *stress-strain curves*.

Hooke's law consists of the simple statement that the stress is proportional to the strain. It obviously implies a condition of perfect elasticity, which is true only for stresses less than the elastic limit.

Stress-Strain Curves. A typical stress-strain diagram of hard-drawn copper wire is shown in Fig. 4-2, which represents No. 9 AWG. The curve *ae* is the actual stress-strain curve; *ab* represents the portion which corresponds to true elasticity, or for which Hooke's law holds rigorously; *cd* is the tangent *ae* which fixes the Johnson elastic limit; and the curve *af* represents the set, or permanent elongation due to flow of the metal under stress, being the difference between *ab* and *ae*. A typical stress-strain diagram of hard-drawn aluminum wire, based on data furnished by the Aluminum Company of America, is shown in Fig. 4-3.

Modulus (or Coefficient) of Elasticity. *Modulus (or coefficient) of elasticity* is the ratio of internal stress to the corresponding strain or deformation. It is a characteristic of each material, form (shape or structure), and type of stressing. For deformations involving changes in both volume and shape, special coefficients are used. For conductors under axial tension, the ratio of stress to strain is called *Young's modulus*.

If *F* is the total force or load acting uniformly on the cross section *A*, the stress is *F/A*. If this magnitude of stress causes an elongation *e* in an original length *l*, the strain is *e/l*. Young's modulus is then expressed

$$M = \frac{Fl}{Ae} \quad (4-17)$$

If a material were capable of sustaining an elastic elongation sufficient to make *e* equal to *l*, or such that the elongated length is double the original length, the stress required to produce this result would equal the modulus. This modulus is very useful in computing the sags of overhead conductor spans under loads of various kinds. It is usually expressed in pounds per square inch.

Stranding usually lowers the Young's modulus somewhat, rope-lay stranding to a greater extent than concentric-lay stranding. When a new cable is subjected initially to tension and the loading is

carried up to the maximum working stress, there is an apparent elongation which is greater than the subsequent elongation under the same loading. This is apparently due to the removal of a very slight slackness in the individual wires, causing them to fit closely together and adjust themselves to the conditions of tension in the strand. When a new cable is loaded to the working limit, unloaded, and then reloaded, the value of Young's modulus determined on initial loading may be on the order of one-half to two-thirds of its true value on reloading. The latter figure should approach within a few percent of the modulus determined by test on individual straight wires of the same material.

For those applications where elastic stretching under tension needs consideration, the stress-strain curve should be determined by test, with the precaution not to prestress the cable before test unless it will be prestressed when installed in service. Commercially used values of Young's modulus for conductors are given in Table 4-1.

TABLE 4-1 Young's Moduli for Conductors

Conductor	Young's modulus,* lb/in ²		Reference
	Final [†]	Virtual initial [‡]	
Copper wire, hard-drawn	17.0 · 10 ⁶	14.5 · 10 ⁶	Copper Wire Engineering Assoc.
Copper wire, medium hard-drawn	16.0 · 10 ⁶	14.0 · 10 ⁶	Anaconda Wire and Cable Co.
Copper cable, hard-drawn, 3 and 12 wire	17.0 · 10 ⁶	14.0 · 10 ⁶	Copper Wire Engineering Assoc.
Copper cable, hard-drawn, 7 and 19 wire	17.0 · 10 ⁶	14.5 · 10 ⁶	Copper Wire Engineering Assoc.
Copper cable, medium hard-drawn	15.5 · 10 ⁶	14.0 · 10 ⁶	Anaconda Wire and Cable Co.
Bronze wire, alloy 15	14.0 · 10 ⁶	13.0 · 10 ⁶	Anaconda Wire and Cable Co.
Bronze wire, other alloys	16.0 · 10 ⁶	14.0 · 10 ⁶	Anaconda Wire and Cable Co.
Bronze cable, alloy 15	13.0 · 10 ⁶	12.0 · 10 ⁶	Anaconda Wire and Cable Co.
Bronze cable, other alloys	16.0 · 10 ⁶	14.0 · 10 ⁶	Anaconda Wire and Cable Co.
Copper-clad steel wire	24.0 · 10 ⁶	22.0 · 10 ⁶	Copperweld Steel Co.
Copper-clad steel cable	23.0 · 10 ⁶	20.5 · 10 ⁶	Copperweld Steel Co.
Copper-copper-clad steel cable, type E	19.5 · 10 ⁶	17.0 · 10 ⁶	Copperweld Steel Co.
Copper-copper-clad steel cable, type EK	18.5 · 10 ⁶	16.0 · 10 ⁶	Copperweld Steel Co.
Copper-copper-clad steel cable, type F	18.0 · 10 ⁶	15.5 · 10 ⁶	Copperweld Steel Co.
Copper-copper-clad steel cable, type 2A to 6A	19.0 · 10 ⁶	16.5 · 10 ⁶	Copper Wire Engineering Assoc.
Aluminum wire	10.0 · 10 ⁶		Reynolds Metals Co.
Aluminum cable	9.1 · 10 ⁶	7.3 · 10 ⁶	Reynolds Metals Co.
Aluminum-alloy wire	10.0 · 10 ⁶		Reynolds Metals Co.
Aluminum-alloy cable	9.1 · 10 ⁶	7.3 · 10 ⁶	Reynolds Metals Co.
Aluminum-steel cable, aluminum wire	7.2–9.0 · 10 ⁶		Aluminum Co. of America
Aluminum-steel cable, steel wire	26.0–29.0 · 10 ⁶		Aluminum Co. of America
Aluminum-clad steel wire	23.5 · 10 ⁶	22.0 · 10 ⁶	Copperweld Steel Co.
Aluminum-clad steel cable	23.0 · 10 ⁶	21.5 · 10 ⁶	Copperweld Steel Co.
Aluminum-clad steel-aluminum cable:			
AWAC 5/2	13.5 · 10 ⁶	12.0 · 10 ⁶	Copperweld Steel Co.
AWAC 4/3	15.5 · 10 ⁶	14.0 · 10 ⁶	Copperweld Steel Co.
AWAC 3/4	17.5 · 10 ⁶	16.0 · 10 ⁶	Copperweld Steel Co.
AWAC 2/5	19.0 · 10 ⁶	18.0 · 10 ⁶	Copperweld Steel Co.
Galvanized-steel wire, Class A coating	28.5 · 10 ⁶		Indiana Steel & Wire Co.
Galvanized-steel cable, Class A coating	27.0 · 10 ⁶		Indiana Steel & Wire Co.

Note: 1 lb/in² = 6.895 kPa.

*For stranded cables the moduli are usually less than for solid wire and vary with number and arrangement of strands, tightness of stranding, and length of lay. Also, during initial application of stress, the stress-strain relation follows a curve throughout the upper part of the range of stress commonly used in transmission-line design.

[†]Final modulus is the ratio of stress to strain (slope of the curve) obtained after fully prestressing the conductor. It is used in calculating design or final sags and tensions.

[‡]Virtual initial modulus is the ratio of stress to strain (slope of the curve) obtained during initial sustained loading of new conductor. It is used in calculating initial or stringing sags and tensions.

Young's Modulus for ACSR. The permanent modulus of ACSR depends on the proportions of steel and aluminum in the cable and on the distribution of stress between aluminum and steel. This latter condition depends on temperature, tension, and previous maximum loadings. Because of the interchange of stress between the steel and the aluminum caused by changes of tension and temperature, computer programs are ordinarily used for sag-tension calculations.

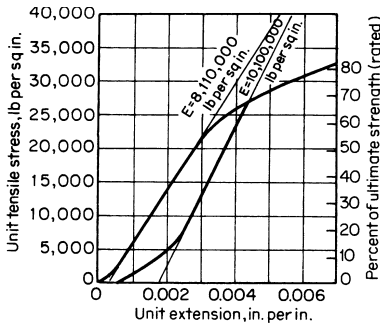


FIGURE 4-4 Repeated stress-strain curve, 795,000 cmil ACSR; 54 $\times$ 0.1212 aluminum strands, 7 $\times$ 0.1212 steel strands.

Because ACSR is a composite cable made of aluminum and steel wires, additional phenomena occur which are not found in tests of cable composed of a single material. As shown in Fig. 4-4, the part of the curve obtained in the second stress cycle contains a comparatively large “foot” at its base, which is caused by the difference in extension at the elastic limits of the aluminum and steel.

Elastic Limit. This is variously defined as the limit of stress beyond which permanent deformation occurs or the stress limit beyond which Hooke's law ceases to apply or the limit beyond which the stresses are not proportional to the strains or the *proportional limit*. In some materials, the elastic limit occurs at a point which is readily determined, but in others it is quite difficult to determine because the stress-strain curve deviates from a straight line but very slightly at first, and the point of departure from true linear

relationship between stress and strain is somewhat indeterminate.

Dean J. B. Johnson of the University of Wisconsin, well-known authority on materials of construction, proposed the use of an arbitrary determination referred to frequently as the *Johnson definition of elastic limit*. This proposal, which has been quite largely used, was that an *apparent elastic limit* be employed, defined as that point on the stress-strain curve at which the rate of deformation is 50% greater than at the origin. The apparent elastic limit thus defined is a practical value, which is suitable for engineering purposes because it involves negligible permanent elongation.

The *Johnson elastic limit* is that point on the stress-strain curve at which the natural tangent is equal to 1.5 times the tangent of the angle of the straight or linear portion of the curve, with respect to the axis of ordinates, or Y axis.

Yield Point. In many materials, a point is reached on the stress-strain diagram at which there is a marked increase in strain or elongation without an increase in stress or load. The point at which this occurs is termed the *yield point*. It is usually quite noticeable in ductile materials but may be scarcely perceptible or possibly not present at all in certain hard-drawn materials such as hard-drawn copper.

Prestressed Conductors. In the case of some materials, especially those of considerable ductility, which tend to show permanent elongation or “drawing” under loads just above the initial elastic limit, it is possible to raise the working elastic limit by loading them to stresses somewhat above the elastic limit as found on initial loading. After such loading, or prestressing, the material will behave according to Hooke's law at all loads less than the new elastic limit. This applies not only to many ductile materials, such as soft or annealed copper wire, but also to cables or stranded conductors, in which there is a slight inherent slack or looseness of the individual wires that can be removed only under actual loading. It is sometimes the practice, when erecting such conductors for service, to prestress them to the working elastic limit or safe maximum working stress and then reduce the stress to the proper value for installation at the stringing temperature without wind or ice.

Resistance. *Resistance* is the property of an electric circuit or of any body that may be used as part of an electric circuit which determines for a given current the average rate at which electrical energy is converted into heat. The term is properly applied only when the rate of conversion is proportional to the square of the current and is then equal to the power conversion divided by the square of

the current. A uniform cylindrical conductor of diameter d , length l , and *volume resistivity* ρ has a total resistance to continuous currents expressed by the formula

$$R = \frac{\rho l}{\pi d^2/4} \quad (4-18)$$

The resistance of any conductor is commonly expressed in ohms per unit of length, such as 1 ft, 1000 ft, or 1 mi. When used for conducting alternating currents, the effective resistance may be higher than the dc resistance defined above. In the latter case, it is a common practice to apply the proper factor, or ratio of effective ac resistance to dc resistance, sometimes termed the *skin-effect resistance ratio*. This ratio may be determined by test, or it may be calculated if the necessary data are available.

Magnetic Permeability. *Magnetic permeability* applies to a field in which the flux is uniformly distributed over a cross section normal to its direction or to a sufficiently small cross section of a nonuniform field so that the distribution can be assumed as substantially uniform. In the case of a cylindrical conductor, the magnetomotive force (mmf) due to the current flowing in the conductor varies from zero at the center or axis to a maximum at the periphery or surface of the conductor and sets up a flux in circular paths concentric with the axis and perpendicular to it but of nonuniform distribution between the axis and the periphery. If the permeability is nonlinear with respect to the mmf, as is usually true with magnetic materials, there is no correct single value of permeability which fits the conditions, although an apparent or equivalent average value can be determined. In the case of other forms of cross section, the distribution is still more complex, and the equivalent permeability may be difficult or impossible to determine except by test.

Internal Inductance. A uniform cylindrical conductor of nonmagnetic material, or of unit permeability, has a constant magnitude of internal inductance per unit length, independent of the conductor diameter. This is commonly expressed in microhenrys or millihenrys per unit of length, such as 1 ft, 1000 ft, or 1 mi. When the conductor material possesses magnetic susceptibility, and when the magnetic permeability μ is constant and therefore independent of the current strength, the internal inductance is expressed in absolute units by the formula

$$L = \frac{\mu l}{2} \quad (4-19)$$

In most cases, μ is not constant but is a function of the current strength. When this is true, there is an effective permeability, one-half of which ($\mu/2$) expresses the inductance per centimeter of length, but this figure of permeability is virtually the ratio of the effective inductance of the conductor of susceptible material to the inductance of a conductor of material which has a permeability of unity. When used for conducting alternating currents, the effective inductance may be less than the inductance with direct current; this is also a direct consequence of the same skin effect which results in an increase of effective resistance with alternating currents, but the overall effect is usually included in the figure of effective permeability. It is usually the practice to determine the effective internal inductance by test, but it may be calculated if the necessary data are available.

Skin Effect. *Skin effect* is a phenomenon which occurs in conductors carrying currents whose intensity varies rapidly from instant to instant but does not occur with continuous currents. It arises from the fact that elements or filaments of variable current at different points in the cross section of a conductor do not encounter equal components of inductance, but the central or axial filament meets the maximum inductance, and in general the inductance offered to other filaments of current decreases as the distance of the filament from the axis increases, becoming a minimum at the surface or periphery of the conductor. This, in turn, tends to produce unequal current density over the cross section as a whole; the density is a minimum at the axis and a maximum at the periphery. Such distribution of the current density produces an increase in effective resistance and a decrease in effective internal inductance; the former is of more practical importance than the latter. In the case of large copper

conductors at commercial power frequencies and in the case of most conductors at carrier and radio frequencies, the increase in resistance should be considered.

Skin-Effect Ratios. If R' is the effective resistance of a linear cylindrical conductor to sinusoidal alternating current of given frequency and R is the true resistance with continuous current, then

$$R' = KR \quad \text{ohms} \quad (4-20)$$

where K is determined from Table 4-2 in terms of x . The value of x is given by

$$x = 2\pi a \sqrt{\frac{2f\mu}{\rho}} \quad (4-21)$$

where a is the radius of the conductor in centimeters, f is the frequency in cycles per second, μ is the magnetic permeability of the conductor (here assumed to be constant), and ρ is the resistivity in abohm-centimeters (abohm = $10^{-9} \Omega$).

TABLE 4-2 Skin-Effect Ratios

x	K	K'	x	K	K'	x	K	K'	x	K	K'
0.0	1.00000	1.00000	2.9	1.28644	0.86012	6.6	2.60313	0.42389	17.0	6.26817	0.16614
0.1	1.00000	1.00000	3.0	1.31809	0.84517	6.8	2.67312	0.41171	18.0	6.62129	0.15694
0.2	1.00001	1.00000	3.1	1.35102	0.82975	7.0	2.74319	0.40021	19.0	6.97446	0.14870
0.3	1.00004	0.99998	3.2	1.38504	0.81397	7.2	2.81334	0.38933	20.0	7.32767	0.14128
0.4	1.00013	0.99993	3.3	1.41999	0.79794	7.4	2.88355	0.37902	21.0	7.68091	0.13456
0.5	1.00032	0.99984	3.4	1.45570	0.78175	7.6	2.95380	0.36923	22.0	8.03418	0.12846
0.6	1.00067	0.99966	3.5	1.49202	0.76550	7.8	3.02411	0.35992	23.0	8.38748	0.12288
0.7	1.00124	0.99937	3.6	1.52879	0.74929	8.0	3.09445	0.35107	24.0	8.74079	0.11777
0.8	1.00212	0.99894	3.7	1.56587	0.73320	8.2	3.16480	0.34263	25.0	9.09412	0.11307
0.9	1.00340	0.99830	3.8	1.60314	0.71729	8.4	3.23518	0.33460	26.0	9.44748	0.10872
1.0	1.00519	0.99741	3.9	1.64051	0.70165	8.6	3.30557	0.32692	28.0	10.15422	0.10096
1.1	1.00758	0.99621	4.0	1.67787	0.68632	8.8	3.37597	0.31958	30.0	10.86101	0.09424
1.2	1.01071	0.99465	4.1	1.71516	0.67135	9.0	3.44638	0.31257	32.0	11.56785	0.08835
1.3	1.01470	0.99266	4.2	1.75233	0.65677	9.2	3.51680	0.30585	34.0	12.27471	0.08316
1.4	1.01969	0.99017	4.3	1.78933	0.64262	9.4	3.58723	0.29941	36.0	12.98160	0.07854
1.5	1.02582	0.98711	4.4	1.82614	0.62890	9.6	3.65766	0.29324	38.0	13.68852	0.07441
1.6	1.03323	0.98342	4.5	1.86275	0.61563	9.8	3.72812	0.28731	40.0	14.39545	0.07069
1.7	1.04205	0.97904	4.6	1.89914	0.60281	10.0	3.79857	0.28162	42.0	15.10240	0.06733
1.8	1.05240	0.97390	4.7	1.93533	0.59044	10.5	3.97477	0.26832	44.0	15.80936	0.06427
1.9	1.06440	0.96795	4.8	1.97131	0.57852	11.0	4.15100	0.25622	46.0	16.51634	0.06148
2.0	1.07816	0.96113	4.9	2.00710	0.56703	11.5	4.32727	0.24516	48.0	17.22333	0.05892
2.1	1.09375	0.95343	5.0	2.04272	0.55597	12.0	4.50358	0.23501	50.0	17.93032	0.05656
2.2	1.11126	0.94482	5.2	2.11353	0.53506	12.5	4.67993	0.22567	60.0	21.46541	0.04713
2.3	1.13069	0.93527	5.4	2.18389	0.51566	13.0	4.85631	0.21703	70.0	25.00063	0.04040
2.4	1.15207	0.92482	5.6	2.25393	0.49764	13.5	5.03272	0.20903	80.0	28.53593	0.03535
2.5	1.17538	0.91347	5.8	2.32380	0.48086	14.0	5.20915	0.20160	90.0	32.07127	0.03142
2.6	1.20056	0.90126	6.0	2.39359	0.46521	14.5	5.38560	0.19468	100.0	35.60666	0.02828
2.7	1.22753	0.88825	6.2	2.46338	0.45056	15.0	5.56208	0.18822	∞	∞	0
2.8	1.25620	0.87451	6.4	2.53321	0.43682	16.0	5.91509	0.17649			

For practical calculation, Eq. (4-21) can be written

$$x = 0.063598 \sqrt{\frac{f\mu}{R}} \quad (4-22)$$

where R is dc resistance at operating temperature in ohms per mile.

If L' is the effective inductance of a linear conductor to sinusoidal alternating current of a given frequency, then

$$L' = L_1 + K'L_2 \quad (4-23)$$

where L_1 is external portion of inductance, L_2 is internal portion (due to the magnetic field within the conductor), and K' is determined from Table 4-2 in terms of x . Thus, the total effective inductance per unit length of conductor is

$$L' = 2 \ln \frac{d}{a} + K' \frac{\mu}{2} \quad (4-24)$$

The inductance is here expressed in abhenrys per centimeter of conductor, in a linear circuit; a is the radius of the conductor, and d is the separation between the conductor and its return conductor, expressed in the same units.

Values of K and K' in terms of x are shown in Table 4-2 and Figs. 4-5 and 4-6 (see *NBS Circ. 74*, pp. 309–311, for additional tables, and *Sci. Paper 374*).

Value of μ for nonmagnetic materials (copper, aluminum, etc.) is 1; for magnetic materials, it varies widely with composition, processing, current density, etc., and should be determined by test in each case.

Alternating-Current Resistance. For small conductors at power frequencies, the frequency has a negligible effect, and dc resistance values can be used. For large conductors, frequency must be taken into account in addition to temperature effects. To do this, first calculate the dc resistance at the operating temperature, then determine the skin-effect ratio K , and finally determine the ac resistance at operating temperature.

AC resistance for copper conductors *not* in close proximity can be obtained from the skin-effect ratios given in Tables 4-2 and 4-3.

AC Resistance for Aluminum Conductors. The increase in resistance and decrease in internal inductance of cylindrical aluminum conductors can be determined from data. It is not the same as for copper conductors of equal diameter but is slightly less because of the higher volume resistivity of aluminum.

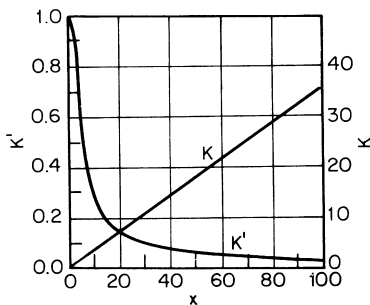


FIGURE 4-5 K and K' for values of x from 0 to 100.

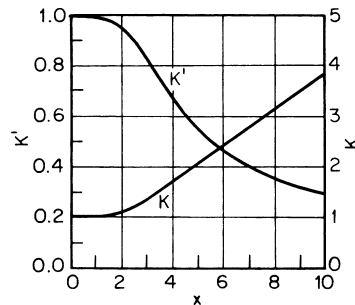


FIGURE 4-6 K and K' for values of x from 0 to 10.

TABLE 4-3 Skin-Effect Ratios—Copper Conductors *Not* in Close Proximity

Skin-effect ratio <i>K</i> at 60 cycles and 65°C (149°F)																		
			Inside conductor diameter, in															
			0"		0.25		0.50		0.75		1.00		1.25		1.30		2.00	
Conductor size, Mcm	Outside diameter, in	<i>K</i>	Outside diameter, in	<i>K</i>	Outside diameter, in	<i>K</i>	Outside diameter, in	<i>K</i>	Outside diameter, in	<i>K</i>	Outside diameter, in	<i>K</i>	Outside diameter, in	<i>K</i>	Outside diameter, in	<i>K</i>	Outside diameter, in	<i>K</i>
	1.998	1.439	2.02	1.39	2.08	1.36	2.15	1.29	2.27	1.23	2.39	1.19	2.54	1.15	2.87	1.08		
	1.825	1.336	1.87	1.28	1.91	1.24	2.00	1.20	2.12	1.16	2.25	1.12	2.40	1.09	2.75	1.05		
	1.631	1.239	1.67	1.20	1.72	1.17	1.80	1.12	1.94	1.09	2.09	1.06	2.25	1.05	2.61	1.02		
	1.412	1.145	1.45	1.12	1.52	1.09	1.63	1.06	1.75	1.04	1.91	1.03	2.07	1.02	2.47	1.01		
	1.152	1.068	1.19	1.05	1.25	1.03	1.39	1.02	1.53	1.01	1.72	1.01						
	1.031	1.046	1.07	1.04	1.16	1.02	1.28	1.01	1.45	1.01								
	0.893	1.026	0.94	1.02	1.04	1.01												
	500	0.814	0.86	1.01	0.97	1.01												
	400	0.728	0.78	1.01														
300	0.630	1.006																

Note: 1 in = 2.54 cm.

*For standard concentric-stranded conductors (i.e., inside diameter = 0).

AC Resistance for ACSR. In the case of ACSR conductors, the steel core is of relatively high resistivity, and therefore its conductance is usually neglected in computing the total resistance of such strands. The effective permeability of the grade of steel employed in the core is also relatively small. It is approximately correct to assume that such a strand is hollow and consists exclusively of its aluminum wires; in this case, the laws of skin effect in tubular conductors will be applicable. Conductors having a single layer of aluminum wires over the steel core have higher ac/dc ratios than those having multiple layers of aluminum wires.

Inductive Reactance. Present practice is to consider inductive reactance as split into two components: (1) that due to flux within a radius of 1 ft including the internal reactance within the conductor of radius r and (2) that due to flux between 1 ft radius and the equivalent conductor spacing D_s or geometric mean distance (GMD). The fundamental inductance formula is

$$L = 2 \ln \frac{D_s}{r} + \frac{\mu}{2} \quad \text{abH/(cm)(conductor)} \quad (4-25)$$

This can be rewritten

$$L = 2 \ln \frac{D_s}{1} + 2 \ln \frac{1}{r} + \frac{\mu}{2} \quad (4-26)$$

where the term $2 \ln (D_s/1)$ represents inductance due to flux between 1 ft radius and the equivalent conductor spacing, and $2 \ln (1/r) + (\mu/2)$ represents the inductance due to flux within 1 ft radius [$2 \ln (1/r)$ represents inductance due to flux between conductor surface and 1 ft radius, and $\mu/2$ represents internal inductance due to flux within the conductor].

By definition, *geometric mean radius* (GMR) of a conductor is the radius of an infinitely thin tube having the same internal inductance as the conductor. Therefore,

$$L = 2 \ln \frac{D_s}{1} + 2 \ln \frac{1}{\text{GMR}} \quad (4-27)$$

Since inductive reactance $= 2\pi fL$, for practical calculation Eq. (4-27) can be written

$$X = 0.004657 f \log \frac{D_s}{1} + 0.004657 f \log \frac{1}{\text{GMR}} \quad \Omega/(\text{mi})(\text{conductor}) \quad (4-28)$$

In the conductor tables in this section, inductive reactance is calculated from Eq. (4-28), considering that

$$X = x_a + x_d \quad (4-29)$$

Inductive reactance for conductors using steel varies in a manner similar to ac resistance.

Capacitive Reactance. The capacitive reactance can be considered in two parts also, giving

$$X = \frac{4.099}{f} \log \frac{D_s}{1} + \frac{4.099}{f} \log \frac{1}{r} \quad \text{M}\Omega/(\text{mi})(\text{conductor}) \quad (4-30)$$

In the conductor tables in this section, capacitive reactance is calculated from Eq. (4-30), it being considered that

$$X' = x'_a + x'_d \quad (4-31)$$

It is important to note that in capacitance calculations the conductor radius used is the actual physical radius of the conductor.

Capacitive Susceptance

$$B = \frac{1}{x'_a + x'_d} \quad \mu\text{S(mi)(conductor)} \quad (4-32)$$

Charging Current

$$I_C = eB \times 10^{-3} \quad \text{A/(mi)(conductor)} \quad (4-33)$$

where e is voltage to neutral in kilovolts.

Bus Conductors. *Bus conductors* require that greater attention be given to certain physical and electrical characteristics of the metals than is usually necessary in designing line conductors. These characteristics are current-carrying capacity, emissivity, skin effect, expansion, and mechanical deflection. To obtain the most satisfactory and economical designs for bus bars in power stations and substations, where they are used extensively, consideration must be given to choice not only of material but also of shape. Both copper and aluminum are used for bus bars, and in certain outdoor substations, steel has proved satisfactory. The most common bus bar form for carrying heavy current, especially indoors, is flat copper bar. Bus bars in the form of angles, channels, and tubing have been developed for heavy currents and, because of better distribution of the conducting material, make more efficient use of the metal both electrically and mechanically. All such designs are based on the need for proper current-carrying capacity without excess bus bar temperatures and on the necessity for adequate mechanical strength.

Hollow (Expanded) Conductors. Hollow (expanded) conductors are used on high-voltage transmission lines when, in order to reduce corona loss, it is desirable to increase the outside diameter without increasing the area beyond that needed for maximum line economy. Not only is the initial corona voltage considerably higher than for conventional conductors of equal cross section, but the current-carrying capacity for a given temperature rise is also greater because of the larger surface area available for cooling and the better disposition of the metal with respect to skin effect when carrying alternating currents.

Air-expanded ACSR is a conductor whose diameter has been increased by aluminum skeletal wires between the steel core and the outer layers of aluminum strands creating air spaces. A conductor having the necessary diameter to minimize corona effects on lines operating above 300 kV will, many times, have more metal than is economical if the conductor is made conventionally.

Composite Conductors. *Composite conductors* are those made up of usually two different types of wire having differing characteristics. They are generally designed for a ratio of physical and electrical characteristics different from those found in homogeneous materials. *Aluminum conductors, steel reinforced (ACSR)* and *aluminum conductors, aluminum alloy reinforced (ACAR)* are types commonly used in overhead transmission and distribution lines.

Cables of this type are particularly adaptable to long-span construction or other service conditions requiring more than average strength combined with liberal conductance. They lend themselves readily to economical, dependable use on transmission lines, rural distribution lines, railroad electrification, river crossings, and many kinds of special construction.

Self-damping ACSR conductors are used to limit aeolian vibration to a safe level regardless of conductor tension or span length. They are concentrically stranded conductors composed of two layers of trapezoidal-shaped wires or two layers of trapezoidal-shaped wires and one layer of round wires of 1350 (EC) alloy with a high-strength, coated steel core. The trapezoidal wire layers are self-supporting, and separated by gaps from adjacent layers (Fig. 4-7). Impact between layers during aeolian vibration causes damping action.

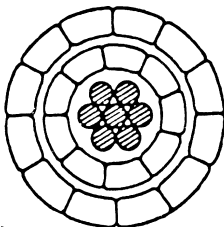


FIGURE 4-7 Self-damping ACSR conductor.

ACSR/TW is similar to self-damping ACSR in its use of trapezoidal-shaped wires, but does not have the annular gaps between layers. ACSR/TW has a smaller diameter and smoother surface than conventional round-wire ACSR of the same area, and thus may have reduced wind loading.

T2 conductors are fabricated by twisting two conventional conductors together with a pitch of about 9 ft (2.7 m). Severity of wind-induced galloping when the conductor is coated with ice is reduced because an ice profile that is uniform along the conductor length cannot form on the variable profile presented by the conductor.

Steel-supported aluminum conductors (SSAC) are similar to conventional ACSR but employ an aluminum alloy in the annealed condition. The annealed aluminum has increased electrical conductivity, and the conductor has improved sag-tension characteristics for high-temperature service.

4.1.4 Fusible Metals and Alloys

Fusible alloys having melting points in the range from about 60 to 200°C are made principally of bismuth, cadmium, lead, and tin in various proportions. Many of these alloys have been known under the names of their inventors (see index of alloys in *International Critical Tables*, vol. 2).

Fuse metals for electric fuses of the open-link enclosed and expulsion types are ordinarily made of some low-fusible alloy; aluminum also is used to some extent. The resistance of the fuse causes dissipation of energy, liberation of heat, and rise of temperature. Sufficient current obviously will melt the fuse, and thus open the circuit if the resulting arc is self-extinguishing. Metals which volatilize readily in the heat of the arc are to be preferred to those which leave a residue of globules of hot metal. The rating of any fuse depends critically on its shape, dimensions, mounting, enclosure, and any other factors which affect its heat-dissipating capacity.

Fusing currents of different kinds of wire were investigated by W. H. Preece, who developed the formula

$$I = ad^{3/2} \quad (4-34)$$

where I is fusing current in amperes, d is diameter of the wire in inches, and a is a constant depending on the material. He found the following values for a :

Copper	10,244	Iron	3,148
Aluminum	7,585	Tin	1,642
Platinum	5,172	Alloy (2Pb-1Sn)	1,318
German silver	5,230	Lead	1,379
Platinoid	4,750		

Although this formula has been used to a considerable extent in the past, it gives values that usually are erroneous in practice because it is based on the assumption that all heat loss is due to radiation. A formula of the general type

$$I = kd^n \quad (4-35)$$

can be used with accuracy if k and n are known for the particular case (material, wire size, installation conditions, etc.).

Fusing current-time for copper conductors and connections may be determined by an equation developed by I. M. Onderdonk

$$33\left(\frac{I}{A}\right)^2 S = \log\left(\frac{T_m - T_a}{234 + T_a} + 1\right) \quad (4-36)$$

$$I = A \sqrt{\frac{\log\left(\frac{T_m - T_a}{234 + T_a} + 1\right)}{33S}} \quad (4-37)$$

where I is current in amperes, A is conductor area in circular mils, S is time current applied in seconds, T_m is melting point of copper in degrees Celsius, and T_a is ambient temperature in degrees Celsius.

4.1.5 Miscellaneous Metals and Alloys

Contact Metals. *Contact metals* may be grouped into three general classifications:

Hard metals, which have high melting points, for example, tungsten and molybdenum. Contacts of these metals are employed usually where operations are continuous or very frequent and current has nominal value of 5 to 10 A. Hardness to withstand mechanical wear and high melting point to resist arc erosion and welding are their outstanding advantages. A tendency to form high-resistance oxides is a disadvantage, but this can be overcome by several methods, such as using high-contact force, a hammering or wiping action, and a properly balanced electric circuit.

Highly conductive metals, of which silver is the best for both electric current and heat. Its disadvantages are softness and a tendency to pit and transfer. In sulfurous atmosphere, a resistant sulfide surface will form on silver, which results in high contact-surface resistance. These disadvantages are overcome usually by alloying.

Noncorroding metals, which for the most part consist of the noble metals, such as gold and the platinum group. Contacts of these metals are used on sensitive devices, employing extremely light pressures or low current in which clean contact surfaces are essential. Because most of these metals are soft, they are usually alloyed.

The metals commonly used are tungsten, molybdenum, platinum, palladium, gold, silver, and their alloys. Alloying materials are copper, nickel, cadmium, iron, and the rarer metals such as iridium and ruthenium. Some are prepared by powder metallurgy.

Tungsten. *Tungsten* (W) is a hard, dense, slow-wearing metal, a good thermal and electrical conductor, characterized by its high melting point and freedom from sticking or welding. It is manufactured in several grades having various grain sizes.

Molybdenum. *Molybdenum* (Mo) has contact characteristics about midway between tungsten and fine silver. It often replaces either metal where greater wear resistance than that of silver or lower contact-surface resistance than that of tungsten is desired.

Platinum. *Platinum* (Pt) is one of the most stable of all metals under the combined action of corrosion and electrical erosion. It has a high melting point and does not corrode and surfaces remain clean and low in resistance under most adverse atmospheric and electrical conditions. *Platinum alloys* of iridium (Ir), ruthenium (Ru), silver (Ag), or other metals are used to increase hardness and resistance to wear.

Palladium. *Palladium* (Pd) has many of the properties of platinum and is frequently used as an alternate for platinum and its alloys. *Palladium alloys* of silver (Ag), ruthenium (Ru), nickel (Ni), and other metals are used to increase hardness and resistance to wear.

Gold. *Gold* (Au) is similar to platinum in corrosion resistance but has a much lower melting point. Gold and its alloys are ductile and easily formed into a variety of shapes. Because of its softness, it is usually alloyed. *Gold alloys* of silver (Ag) and other metals are used to impart hardness and improve resistance to mechanical wear and electrical erosion.

Silver. *Silver* (Ag) has the highest thermal and electrical conductivity (110%, IACS) of any metal. It has low contact-surface resistance, since its oxide decomposes at approximately 300°F. It is available commercially in three grades:

Grade	Typical composition, %	
	Silver	Copper
Fine silver	99.95+	
Sterling silver	92.5	7.5
Coin silver	90	10

Fine silver is used extensively under low contact pressure where sensitivity and low contact-surface resistance are essential or where the circuit is operated infrequently.

Sterling and coin silvers are harder than fine silver and resist transfer at low voltage (6 to 8 V) better than fine silver. Since their contact-surface resistance is greater than that of fine silver, higher contact-closing forces should be used.

Silver alloys of copper (Cu), nickel (Ni), cadmium (Cd), iron (Fe), carbon (C), tungsten (W), molybdenum (Mo), and other metals are used to improve hardness, resistance to wear and arc erosion, and for special applications.

Selenium. *Selenium* is a nonmetallic element chemically resembling sulfur and tellurium and occurs in several allotropic forms varying in specific gravity from 4.3 to 4.8. It melts at 217°C and boils at 690°C. At 0°C, it has a resistivity of approximately 60,000 $\Omega \cdot \text{cm}$. The dielectric constant ranges from 6.1 to 7.4. It has the peculiar property that its resistivity decreases on exposure to light; the resistivity in darkness may be anywhere from 5 to 200 times the resistivity under exposure to light.

4.2 MAGNETIC MATERIALS

4.2.1 Definitions

The following definitions of terms relating to magnetic materials and the properties and testing of these materials have been selected from ASTM Standard. Terms primarily related to magnetostatics are indicated by the symbol * and those related to magnetodynamics are indicated by the symbol **. General (nonrestricted) terms are not marked.

***AC Excitation* $N_p I / l_p$. The ratio of the rms ampere-turns of exciting current in the primary winding of an inductor to the effective length of the magnetic path.

***Active (Real) Power* P . The product of the rms current I in an electric circuit, the rms voltage E across the circuit, and the cosine of the angular phase difference θ between the current and the voltage.

$$P = EI \cos \theta \quad (4-38)$$

NOTE: The portion of the active power that is expended in a magnetic core is the total core loss P_c .

Aging, Magnetic. The change in the magnetic properties of a material resulting from metallurgical change. This term applies whether the change results from a continued normal or a specified accelerated aging condition.

NOTE: This term implies a deterioration of the magnetic properties of magnetic materials for electronic and electrical applications, unless otherwise specified.

Ampere-turn. Unit of magnetomotive force in the rationalized mksa system. One ampere-turn equals $4\pi/10$, or 1.257 gilberts.

Ampere-turn per Meter. Unit of magnetizing force (magnetic field strength) in the rationalized mksa system. One ampere-turn per meter is $4\pi \times 10^{-3}$, or 0.01257 oersted.

Anisotropic Material. A material in which the magnetic properties differ in various directions.

Antiferromagnetic Material. A feebly magnetic material in which almost equal magnetic moments are lined up antiparallel to each other. Its susceptibility increases as the temperature is raised until a critical (Neél) temperature is reached; above this temperature the material becomes paramagnetic.

****Apparent Power P_a .** The product (volt-amperes) of the rms exciting current and the applied rms terminal voltage in an electric circuit containing inductive impedance. The components of this impedance due to the winding will be linear, while the components due to the magnetic core will be nonlinear.

****Apparent Power; Specific, $P_{a(B,f)}$.** The value of the apparent power divided by the active mass of the specimen (volt-amperes per unit mass) taken at a specified maximum value of cyclically varying induction B and at a specified frequency f .

***Coercive Force H_c .** The (dc) magnetizing force at which the magnetic induction is zero when the material is in a symmetrically cyclically magnetized condition.

***Coercive Force, Intrinsic, H_{ci} .** The (dc) magnetizing force at which the intrinsic induction is zero when the material is in a symmetrically cyclically magnetized condition.

***Coercivity H_{cs} .** The maximum value of coercive force.

****Core Loss; Specific, $P_{c(B,f)}$.** The active power (watts) expended per unit mass of magnetic material in which there is a cyclically varying induction of a specified maximum value B at a specified frequency f .

****Core Loss (Total) P_c .** The active power (watts) expended in a magnetic circuit in which there is a cyclically alternating induction.

NOTE: Measurements of core loss are normally made with sinusoidally alternating induction, or the results are corrected for deviations from the sinusoidal condition.

Curie Temperature T_c . The temperature above which a ferromagnetic material becomes paramagnetic.

***Demagnetization Curve.** That portion of a normal (dc) hysteresis loop which lies in the second or fourth quadrant, that is, between the residual induction point B_r and the coercive force point H_c . Points on this curve are designated by the coordinates B_d and H_d .

Diamagnetic Material. A material whose relative permeability is less than unity.

NOTE: The intrinsic induction B_p is oppositely directed to the applied magnetizing force H .

Domains, Ferromagnetic. Magnetized regions, either macroscopic or microscopic in size, within ferromagnetic materials. Each domain per se is magnetized to intrinsic saturation at all times, and this saturation induction is unidirectional within the domain.

****Eddy-Current Loss, Normal, P_e .** That portion of the core loss which is due to induced currents circulating in the magnetic material subject to an SCM excitation.

***Energy Product $B_d H_d$.** The product of the coordinate values of any point on a demagnetization curve.

***Energy-Product Curve, Magnetic.** The curve obtained by plotting the product of the corresponding coordinates B_d and H_d of points on the demagnetization curve as abscissa against the induction B_d as ordinates.

NOTE 1: The maximum value of the energy product $(B_d H_d)_m$ corresponds to the maximum value of the external energy.

NOTE 2: The demagnetization curve is plotted to the left of the vertical axis and usually the energy-product curve to the right.

****Exciting Power, rms, P_z .** The product of the rms exciting current and the rms voltage induced in the exciting (primary) winding on a magnetic core.

NOTE: This is the apparent volt-amperes required for the excitation of the magnetic core only. When the core has a secondary winding, the induced primary voltage is obtained from the measured open-circuit secondary voltage multiplied by the appropriate turns ratio.

****Exciting Power, Specific $P_{(B,f)}$** The value of the rms exciting power divided by the active mass of the specimen (volt-amperes/unit mass) taken at a specified maximum value of cyclically varying induction B and at specified frequency f .

Ferrimagnetic Material. A material in which unequal magnetic moments are lined up antiparallel to each other. Permeabilities are of the same order of magnitude as those of ferromagnetic materials, but are lower than they would be if all atomic moments were parallel and in the same direction. Under ordinary conditions, the magnetic characteristics of ferrimagnetic materials are quite similar to those of ferromagnetic materials.

Ferromagnetic Material. A material that, in general, exhibits the phenomena of hysteresis and saturation, and whose permeability is dependent on the magnetizing force.

Gauss (Plural Gausses). The unit of magnetic induction in the cgs electromagnetic system. The gauss is equal to 1 maxwell per square centimeter or 10^{-4} T. See *magnetic induction (flux density)*.

Gilbert. The unit of magnetomotive force in the cgs electromagnetic system. The gilbert is a magnetomotive force of $10/4\pi$ ampere-turns. See *magnetomotive force*.

***Hysteresis Loop, Intrinsic.** A hysteresis loop obtained with a ferromagnetic material by plotting (usually to rectangular coordinates) corresponding dc values of intrinsic induction B_i for ordinates and magnetizing force H for abscissas.

***Hysteresis Loop, Normal.** A closed curve obtained with a ferromagnetic material by plotting (usually to rectangular coordinates) corresponding dc values of magnetic induction B for ordinates and magnetizing force H for abscissas when the material is passing through a complete cycle between equal definite limits of either magnetizing force $\pm H_m$ or magnetic induction $\pm B_m$. In general, the normal hysteresis loop has mirror symmetry with respect to the origin of the B and H axes, but this may not be true for special materials.

***Hysteresis-Loop Loss W_h .** The energy expended in a single slow excursion around a normal hysteresis loop is given by the following equation:

$$W_h = \int \frac{HdB}{4\pi} \quad \text{ergs} \quad (4-39)$$

where the integrated area enclosed by the loop is measured in gauss-oersteds.

****Hysteresis Loss, Normal, P_h .**

1. The power expended in a ferromagnetic material, as a result of hysteresis, when the material is subjected to an *SCM* excitation.
2. The energy loss/cycle in a magnetic material as a result of magnetic hysteresis when the induction is cyclic (but not necessarily periodic).

Hysteresis, Magnetic The property of a ferromagnetic material exhibited by the lack of correspondence between the changes in induction resulting from increasing magnetizing force from decreasing magnetizing force.

Induction B . See *magnetic induction (flux density)*.

***Induction, Intrinsic, B_i .** The vector difference between the magnetic induction in a magnetic material and the magnetic induction that would exist in a vacuum under the influence of the same magnetizing force. This is expressed by the equation

$$B_i = B - \Gamma_m H \quad (4-40)$$

NOTE: In the cgs-em system, $B/4\pi$ is often called *magnetic polarization*.

Induction Maximum

- *1. B_m —the maximum value of B in a hysteresis loop. The tip of this loop has the magnetostatic coordinates H_m , B_m , which exist simultaneously.
- **2. $B_{\max}$ —the maximum value of induction, in a flux-current loop.

NOTE: In a flux-current loop, the magnetodynamic values $B_{\max}$ and $H_{\max}$ do not exist simultaneously; $B_{\max}$ occurs later than $H_{\max}$.

**Induction, Normal, B .* The maximum induction in a magnetic material that is in a symmetrically cyclically magnetized condition.

NOTE: Normal induction is a magnetostatic parameter usually measured by hallistic methods.

**Induction, Remanent, B_d .* The magnetic induction that remains in a magnetic circuit after the removal of an applied magnetomotive force.

NOTE: If there are no air gaps or other inhomogeneities in the magnetic circuit, the remanent induction B_r will equal the residual induction B_r ; if air gaps or other inhomogeneities are present, B_d will be less than B_r .

**Induction, Residual, B_r .* The magnetic induction corresponding to zero magnetizing force in a magnetic material that is in a symmetrically cyclically magnetized condition.

**Induction, Saturation, B_s .* The maximum intrinsic induction possible in a material.

**Induction Curve, Intrinsic (Ferric).* A curve of a previously demagnetized specimen depicting the relation between intrinsic induction and corresponding ascending values of magnetizing force. This curve starts at the origin of the B_i and H axes.

**Induction Curve, Normal.* A curve of a previously demagnetized specimen depicting the relation between normal induction and corresponding ascending values of magnetizing force. This curve starts at the origin of the B and H axes.

Isotropic Material. Material in which the magnetic properties are the same for all directions.

Magnetic Circuit. A region at whose surface the magnetic induction is tangential.

NOTE: A practical magnetic circuit is the region containing the flux of practical interest, such as the core of a transformer. It may consist of ferromagnetic material with or without air gaps or other feebly magnetic materials such as porcelain and brass.

Magnetic Constant (Permeability of Space) Γ_m . The dimensional scalar factor that relates the mechanical force between two currents to their intensities and geometrical configurations. That is,

$$dF = \Gamma_m I_1 I_2 dl_1 \times \frac{dl_2 \times r_1}{nr^2} \quad (4-41)$$

where Γ_m = magnetic constant when the element of force dF of a current element $I_1 dl_1$ on another current element $I_2 dl_2$ is at a distance r

r_1 = unit vector in the direction from dl_1 to dl_2

n = dimensionless factor, the symbol n is unity in unrationalized systems and 4π in rationalized systems

NOTE 1: The numerical values of Γ_m depend on the system of units employed. In the cgs-em system, $\Gamma_m = 1$; in the rationalized mksa system, $\Gamma_m = 4\pi \times 10^{-7}$ h/m.

NOTE 2: The magnetic constant expresses the ratio of magnetic induction to the corresponding magnetizing force at any point in a vacuum and therefore is sometimes called the permeability of space μ_r .

NOTE 3: The magnetic constant times the relative permeability is equal to the absolute permeability:

$$\mu_{\text{abs}} = \Gamma_m \mu_r \quad (4-42)$$

Magnetic Field Strength H . See magnetizing force.

Magnetic Flux ϕ . The product of the magnetic induction B and the area of a surface (or cross section) A when the magnetic induction B is uniformly distributed and normal to the plane of the surface.

$$\phi = BA \quad (4-43)$$

where ϕ = magnetic flux
 B = magnetic induction
 A = area of the surface

NOTE 1: If the magnetic induction is not uniformly distributed over the surface, the flux ϕ is the surface integral of the normal component of B over the area:

$$\phi = \iint_s B \, dA \quad (4-44)$$

NOTE 2: Magnetic flux is scalar and has no direction.

Magnetic Flux Density B . See magnetic induction (flux density).

Magnetic Induction (Flux Density) B . That magnetic vector quantity which at any point in a magnetic field is measured either by the mechanical force experienced by an element of electric current at the point, or by the electromotive force induced in an elementary loop during any change in flux linkages with the loop at the point.

NOTE 1: If the magnetic induction B is uniformly distributed and normal to a surface or cross section, then the magnetic induction is

$$B = \phi/A \quad (4-45)$$

where B = magnetic induction
 ϕ = total flux
 A = area

NOTE 2: B_m is the instantaneous value of the magnetic induction and B_m is the maximum value of the magnetic induction.

Magnetizing Force (Magnetic Field Strength) H . That magnetic vector quantity at a point in a magnetic field which measures the ability of electric currents or magnetized bodies to produce magnetic induction at the given point.

NOTE 1: The magnetizing force H may be calculated from the current and the geometry of certain magnetizing circuits. For example, in the center of a uniformly wound long solenoid,

$$H = C(NI/l) \quad (4-46)$$

where H = magnetizing force
 C = constant whose value depends on the system of units
 N = number of turns
 I = current
 l = axial length of the coil

If I is expressed in amperes and l is expressed in centimeters, then $C = 4\pi/10$ in order to obtain H in the cgs = em unit, the oersted. If I is expressed in amperes and l is expressed in meters, then $C = 1$ in order to obtain H in the mksa unit, ampere-turn per meter.

NOTE 2: The magnetizing force H at a point in air may be calculated from the measured value of induction at the point by dividing this value by the magnetic constant Γ_m .

****Magnetizing Force, AC.** Three different values of dynamic magnetizing force parameters are in common use:

1. H_L —an assumed peak value computed in terms of peak magnetizing current (considered to be sinusoidal).
2. H_x —an assumed peak value computed in terms of measured rms exciting current (considered to be sinusoidal).
3. H_p —computed in terms of a measured peak value of exciting current, and thus equal to the value $H'_{\max}$.

****Magnetodynamic.** The magnetic condition when the values of magnetizing force and induction vary, usually periodically and repetitively, between two extreme limits.

Magnetomotive Force F . The line integral of the magnetizing force around any flux loop in space.

$$F = \oint H \, dl \quad (4-47)$$

where F = magnetomotive force

H = magnetizing force

dl = unit length along the loop

NOTE: The magnetomotive force is proportional to the net current linked with any closed loop of flux or closed path

$$F = CNI \quad (4-48)$$

where F = magnetomotive force

N = number of turns linked with the loop

I = current in amperes

C = constant whose value depends on the system of units. In the cgs system, $C = 4\pi/10$. In the mksa system, $C = 1$

***Magnetostatic.** The magnetic condition when the values of magnetizing force and induction are considered to remain invariant with time during the period of measurement. This is often referred to as a dc (direct-current) condition.

Magnetostriction. Changes in dimensions of a body resulting from magnetization.

Maxwell. The unit of magnetic flux in the cgs electromagnetic system. One maxwell equals 10^{-8} weber. See *magnetic flux*.

NOTE:

$$e = -N \frac{d\phi}{dt} \times 10^{-8} \quad (4-49)$$

where e = induced instantaneous emf volts

$d\phi/dt$ = time rate of change of flux, maxwells per second

N = number of turns surrounding the flux, assuming each turn is linked with all the flux

Oersted. The unit of magnetizing force (magnetic field strength) in the cgs electromagnetic system. One oersted equals a magnetomotive force of 1 gilbert/cm of flux path. One oersted equals $100/4\pi$ or 79.58 ampere-turns per meter. See *magnetizing force (magnetic field strength)*.

Paramagnetic Material. A material having a relative permeability which is slightly greater than unity, and which is practically independent of the magnetizing force.

****Permeability, AC .** A generic term used to express various dynamic relationships between magnetic induction B and magnetizing force H for magnetic material subjected to a cyclic excitation by alternating or pulsating current. The values of ac permeability obtained for a given material depend fundamentally on the excursion limits of dynamic excitation and induction, the method and conditions of measurement, and also on such factors as resistivity, thickness of laminations, frequency of excitation, etc.

NOTE: The numerical value for any permeability is meaningless unless the corresponding B or H excitation level is specified. For incremental permeabilities, not only the corresponding dc B or H excitation level must be specified but also the dynamic excursion limits of dynamic excitation range (ΔB or ΔH).

AC permeabilities in common use for magnetic testing are

1. ****Impedance (rms) permeability μ_z .** The ratio of the measured peak value of magnetic induction to the value of the apparent magnetizing force H_z , calculated from the measured rms value of the exciting current, for a material in the *SCM* condition.

NOTE: The value of the current used to compute H_z is obtained by multiplying the measured value of rms exciting current by 1.414. This assumes that the total exciting current is magnetizing current and is sinusoidal.

2. ****Inductance permeability μ_L .** For a material in an *SCM* condition, the permeability is evaluated from the measured inductive component of the electric circuit representing the magnetic specimen. This circuit is assumed to be composed of paralleled linear inductive and resistive elements ωL_1 and R_1 .
3. ****Peak permeability μ_p .** The ratio of the measured peak value of magnetic induction to the peak value of the magnetizing force H_p , calculated from the measured peak value of the exciting current, for a material in the *SCM* condition.

Other ac permeabilities are:

4. **Ideal permeability μ_a .** The ratio of the magnetic induction to the corresponding magnetizing force after the material has been simultaneously subjected to a value of ac magnetizing force approaching saturation (of approximate sine waveform) superimposed on a given dc magnetizing force, and the ac magnetizing force has thereafter been gradually reduced to zero. The resulting ideal permeability is thus a function of the dc magnetizing force used.

NOTE: Ideal permeability, sometimes called anhysteretic permeability, is principally significant to feebly magnetic material and to the Rayleigh range of soft magnetic material.

5. ****Impedance, permeability, incremental, $\mu_{\Delta z}$.** Impedance permeability μ_z obtained when an ac excitation is superimposed on a dc excitation, *CM* condition.
6. ****Inductance permeability, incremental, $\mu_{\Delta L}$.** Inductance permeability μ_L obtained when an ac excitation is superimposed on a dc excitation, *CM* condition.
7. ****Initial dynamic permeability μ_{0d} .** The limiting value of inductance permeability μ_L reached in a ferromagnetic core when, under *SCM* excitation, the magnetizing current has been progressively and gradually reduced from a comparatively high value to zero value.

NOTE: This same value, μ_{0d} , is also equal to the initial values of both impedance permeability μ_x and peak permeability μ_p .

8. ****Instantaneous permeability (coincident with $B_{\max}$) μ_r .** With *SCM* excitation, the ratio of the maximum induction $B_{\max}$ to the instantaneous magnetizing force H_r , which is the value of apparent magnetizing force $H^{\max}$ determined at the instant when B reaches a maximum.
9. ****Peak permeability, incremental, $\mu_{\Delta p}$.** Peak permeability μ_p obtained when an ac excitation is superimposed on dc excitation, *CM* condition.

***Permeability, DC.** Permeability is a general term used to express relationships between magnetic induction B and magnetizing force H under various conditions of magnetic excitation. These relationships are either (1) absolute permeability, which in general is the quotient of a change in magnetic induction divided by the corresponding change in magnetizing force, or (2) relative permeability, which is the ratio of the absolute permeability to the magnetic constant Γ_m .

NOTE 1: The magnetic constant Γ_m is a scalar quantity differing in value and uniquely determined by each electromagnetic system of units. In the unrationalized cgs system, Γ_m is 1 gauss/oersted and in the mksa rationalized system $\Gamma_m = 4\pi \times 10^{-7}$ H/m.

NOTE 2: Relative permeability is a pure number which is the same in all unit systems. The value and dimension of absolute permeability depend on the system of units employed.

NOTE 3: For any ferromagnetic material, permeability is a function of the degree of magnetization. However, initial permeability μ_0 and maximum permeability μ_m are unique values for a given specimen under specified conditions.

NOTE 4: Except for initial permeability μ_0 , a numerical value for any of the dc permeabilities is meaningless unless the corresponding B or H excitation level is specified.

NOTE 5: For the incremental permeabilities μ_Δ and $\mu_{\Delta r}$, a numerical value is meaningless unless both the corresponding values of mean excitation level ($\bar{B}$ or $\bar{H}$) and the excursion range (ΔB or ΔH) are specified.

The following dc permeabilities are frequently used in magnetostatic measurements primarily concerned with the testing of materials destined for use with permanent or dc excited magnets:

1. **Absolute permeability μ_{abs}* The sum of the magnetic constant and the intrinsic permeability. It is also equal to the product of the magnetic constant and the relative permeability.

$$\mu_{\text{abs}} = \Gamma_m + \mu_i = \Gamma_m \mu_r \quad (4-50)$$

2. **Differential permeability μ_d* The absolute value of the slope of the hysteresis loop at any point, or the slope of the normal magnetizing curve at any point.
3. **Effective circuit permeability μ_{eff}* When a magnetic circuit consists of two or more components, each individually homogeneous throughout but having different permeability values, the effective (overall) permeability of the circuit is that value computed in terms of the total magnetomotive force, the total resulting flux, and the geometry of the circuit.

NOTE: For a symmetrical series circuit in which each component has the same cross-sectional area, reluctance values add directly, giving

$$\mu_{\text{eff}} = \frac{l_1 + l_2 + l_3 + \cdots}{l_1/\mu_1 + l_2/\mu_2 + l_3/\mu_3 + \cdots} \quad (4-51)$$

For a symmetrical parallel circuit in which each component has the same flux path length, permeance values add directly, giving

$$\mu_{\text{eff}} = \frac{\mu_1 A_1 + \mu_2 A_2 + \mu_3 A_3 + \cdots}{A_1 + A_2 + A_3 + \cdots} \quad (4-52)$$

4. **Incremental intrinsic permeability $\mu_{\Delta i}$* The ratio of the change in intrinsic induction to the corresponding change in magnetizing force when the mean induction differs from zero.
5. **Incremental permeability μ_Δ* The ratio of a change in magnetic induction to the corresponding change in magnetizing force when the mean induction differs from zero. It equals the slope of a straight line joining the excursion limits of an incremental hysteresis loop.

NOTE: When the change in H is reduced to zero, the incremental permeability μ_Δ becomes the reversible permeability μ_{rev} .

6. **Initial permeability μ_0* The limiting value approached by the normal permeability as the applied magnetizing force H is reduced to zero. The permeability is equal to the slope of the normal induction curve at the origin of linear B and H axes.
7. **Intrinsic permeability μ_i* The ratio of intrinsic induction to the corresponding magnetizing force.
8. **Maximum permeability μ_m* The value of normal permeability for a given material where a straight line from the origin of linear B and H axes becomes tangent to the normal induction curve.
9. **Normal permeability μ (without subscript)* The ratio of the normal induction to the corresponding magnetizing force. It is equal to the slope of a straight line joining the extrusion limits

of a normal hysteresis loop, or the slope of a straight line joining any point (H_m, B_m) on the normal induction curve to the origin of the linear B and H axes.

10. **Relative permeability μ_r* . The ratio of the absolute permeability of a material to the magnetic constant Γ_m giving a pure numeric parameter.

NOTE: In the cgs-em system of units, the relative permeability is numerically the same as the absolute permeability.

11. *Reversible permeability μ_{rev}* . The limit of the incremental permeability as the change in magnetizing force approaches zero.
12. *Space permeability μ_o* . The permeability of space (vacuum), identical with the magnetic constant Γ_m .

***Reactive Power (Quadrature Power) P_q* . The product of the rms current in an electric circuit, the rms voltage across the circuit, and the sine of the angular phase difference between the current and the voltage.

$$P_q = EI \sin \theta \quad (4-53)$$

where P_q = reactive power, vars

E = voltage, volts

I = current, amperes

θ = angular phase by which E leads I

NOTE: The reactive power supplied to a magnetic core having an *SCM* excitation is the product of the magnetizing current and the voltage induced in the exciting winding.

**Remanence B_{dm}* . The maximum value of the remanent induction for a given geometry of the magnetic circuit.

NOTE: If there are no air gaps or other inhomogeneities in the magnetic circuit, the remanence B_{dm} is equal to the retentivity B_{rs} ; if air gaps or other inhomogeneities are present, B_{dm} will be less than B_{rs} .

**Retentivity B_{rs}* . That property of a magnetic material which is measured by its maximum value of the residual induction.

NOTE: Retentivity is usually associated with saturation induction.

Symmetrically Cyclically Magnetized Condition, SCM. A magnetic material is in an *SCM* condition when, under the influence of a magnetizing force that varies cyclically between two equal positive and negative limits, its successive hysteresis loops or flux-current loops are both identical and symmetrical with respect to the origin of the axes.

Tesla. The unit of magnetic induction in the mksa (Giorgi) system. The tesla is equal to 1 Wb/m² or 10⁴ gauss.

Var. The unit of reactive (quadrature) power in the mksa (Giorgi) and the practical systems.

Volt-Ampere. The unit of apparent power in the mksa (Giorgi) and the practical systems.

Watt. The unit of active power in the mksa (Giorgi) and the practical systems. One watt is a power of 1 J/s.

Weber. The unit of magnetic flux in the mksa and in the practical system. The weber is the magnetic flux whose decrease to zero when linked with a single turn induces in the turn a voltage whose time integral is 1 v/s. One weber equals 10⁸ maxwells. See *magnetic flux*.

4.2.2 Magnetic Properties and Their Application

The relative importance of the various magnetic properties of a magnetic material varies from one application to another. In general, properties of interest may include normal induction, hysteresis, dc permeability, ac permeability, core loss, and exciting power. It should be noted that there are various means of expressing ac permeability. The choice depends primarily on the ultimate use.

Techniques for the magnetic testing of many magnetic materials are described in the ASTM standards. The magnetic and electric circuits employed in magnetic testing of a specimen are as free as possible from any unfavorable design factors which would prevent the measured magnetic data from being representative of the inherent magnetic properties of the specimen. The flux “direction” in the specimen is normally specified, since most magnetic materials are magnetically anisotropic. In most ac magnetic tests, the waveform of the flux is required to be sinusoidal.

As a result of the existence of unfavorable conditions, such as those listed and described below, the performance of a magnetic material in a magnetic device can be greatly deteriorated from that which would be expected from magnetic testing of the material. Allowances for these conditions, if present, must be made during the design of the device if the performance of the device is to be correctly predicted.

Leakage. A principal difficulty in the design of many magnetic circuits is due to the lack of a practicable material which will act as an insulator with respect to magnetic flux. This results in magnetic flux seldom being completely confined to the desired magnetic circuit. Estimates of leakage flux for a particular design may be made based on experience and/or experimentation.

Flux Direction. Some magnetic materials have a very pronounced directionality in their magnetic properties. Failure to utilize these materials in their preferred directions results in impaired magnetic properties.

Fabrication. Stresses introduced into magnetic materials by the various fabricating techniques often adversely affect the magnetic properties of the materials. This occurs particularly in materials having high permeability. Stresses may be eliminated by a suitable stress-relief anneal after fabrication of the material to final shape.

Joints. Joints in an electromagnetic core may cause a large increase in total excitation requirements. In some cores operated on ac, core loss may also be increased.

Waveform. When a sinusoidal voltage is applied to an electromagnetic core, the resulting magnetic flux is not necessarily sinusoidal in waveform, especially at high inductions. Any harmonics in the flux waveform cause increases in core loss and required excitation power.

Flux Distribution. If the maximum and minimum lengths of the magnetic path in an electromagnetic core differ too much, the flux density may be appreciably greater at the inside of the core structure than at the outside. For cores operated on ac, this can cause the waveform of the flux at the extremes of the core structure to be distorted even when the total flux waveform is sinusoidal.

4.2.3 Types of Magnetism

Any substance may be classified into one of the following categories according to the type of magnetic behavior it exhibits:

1. Diamagnetic
2. Paramagnetic
3. Antiferromagnetic
4. Ferromagnetic
5. Ferrimagnetic

Substances that fall into the first three categories are so weakly magnetic that they are commonly thought of as *nonmagnetic*. In contrast, ferromagnetic and ferrimagnetic substances are strongly magnetic and are thereby of interest as *magnetic materials*. The magnetic behavior of any ferromagnetic or ferrimagnetic material is a result of its spontaneously magnetized magnetic domain structure and is characterized by a nonlinear normal induction curve, hysteresis, and saturation.

The pure elements which are ferromagnetic are iron, nickel, cobalt, and some of the rare earths. Ferromagnetic materials of value to industry for their magnetic properties are almost invariably alloys of the metallic ferromagnetic elements with one another and/or with other elements.

Ferrimagnetism occurs mainly in the ferrites, which are chemical compounds having ferric oxide (Fe_2O_3) as a component. In recent years, some of the magnetic ferrites have become very important

in certain magnetic applications. The magnetic ferrites saturate magnetically at lower inductions than do the great majority of metallic ferromagnetic materials. However, the electrical resistivities of ferrites are at least several orders of magnitude greater than those of metals.

Commercial Magnetic Materials. *Commercial magnetic materials* are generally divided into two main groups, each composed of ferromagnetic and ferrimagnetic substances:

1. Magnetically “soft” materials
2. Magnetically “hard” materials

The distinguishing characteristic of “soft” magnetic materials is high permeability. These materials are employed as core materials in the magnetic circuits of electromagnetic equipment. “Hard” magnetic materials are characterized by a high maximum magnetic energy product $BH_{\max}$. These materials are employed as permanent magnets to provide a constant magnetic field when it is inconvenient or uneconomical to produce the field by electromagnetic means.

4.2.4 “Soft” Magnetic Materials

A wide variety of “soft” magnetic materials have been developed to meet the many different requirements imposed on magnetic cores for modern electrical apparatus and electronic devices. The various soft magnetic materials will be considered under three classifications:

1. Materials for solid cores.
2. Materials for laminated cores.
3. Materials for special purposes.

4.2.5 Materials for Solid Cores

These materials are used in dc applications such as yokes of dc dynamos, rotors of synchronous dynamos, and cores of dc electromagnets and relays. Proper annealing of these materials improves their magnetic properties. The principal magnetic requirements for the solid-core materials are high saturation, high permeability at relatively high inductions, and at times, low coercive force.

Wrought iron is a ferrous material, aggregated from a solidifying mass of pasty particles of highly refined metallic iron, into which is incorporated, without subsequent fusion, a minutely and uniformly distributed quantity of slag. The better types of wrought iron are known as *Norway iron* and *Swedish iron* and are widely used in relays after being annealed to reduce coercive force and to minimize magnetic aging.

Cast irons are irons which contain carbon in excess of the amount which can be retained in solid solution in austenite at the eutectic temperature. The minimum carbon content is about 2%, while the practical maximum carbon content is about 4.5%. Cast iron was used in the yokes of dc dynamos in the early days of such machines.

Gray cast iron is a cast iron in which graphite is present in the form of flakes. It has very poor magnetic properties, inferior mechanical properties, and practically no ductility. It does lend itself well to the casting of complex shapes and is readily machinable.

Malleable cast iron is a cast iron in which the graphite is present as temper carbon nodules. It is magnetically better than gray cast iron.

Ductile (nodular) cast iron is a cast iron with the graphite essentially spheroidal in shape. It is magnetically better than gray cast iron. Ductile cast iron has the good castability and machinability of gray cast iron together with much greater strength, ductility, and shock resistance.

4.2.6 Carbon Steels

Carbon steels may contain from less than 0.1% carbon to more than 1% carbon. The magnetic properties of a carbon steel are greatly influenced by the carbon content and the disposition of the

carbon. Low-carbon steels (less than 0.2% carbon) have magnetic properties which are similar to those of wrought iron and far superior to those of any of the cast irons.

Wrought carbon steels are widely used as solid-core materials. The low-carbon types are preferred in most applications.

Cast carbon steels replaced cast iron many years ago as the material used in the yokes of dc machines, but have since largely been supplanted in this application by wrought (hot-rolled) carbon-steel plates of welding quality.

4.2.7 Materials for Laminated Cores

The materials most widely employed in wound or stacked cores in electromagnetic devices operated at the commercial power frequencies (50 and 60 Hz) are the electrical steels and the specially processed carbon steels designated as *magnetic lamination steels*. The principal magnetic requirements for these materials are low core loss, high permeability, and high saturation. ASTM publishes standard specifications for these materials. On a tonnage basis, production of these materials far exceeds that of any other magnetic material.

Electrical steels are flat-rolled low-carbon silicon-iron alloys. Since applications for electrical steels lie mainly in energy-loss-limited equipment, the core losses of electrical steels are normally guaranteed by the producers. The general category of electrical steels may be divided into classifications of (1) nonoriented materials and (2) grain-oriented materials.

Electrical steels are usually graded by high-induction core loss. Both ASTM and AISI have established and published designation systems for electrical steels based on core loss.

The ASTM core loss type designation consists of six or seven characters. The first two characters are 100 times the nominal thickness of the material in millimeters. The third character is a code letter which designates the class of the material and specifies the sampling and testing practices. The last three or four characters are 100 times the maximum permissible core loss in watts per pound at a specified test frequency and induction.

The AISI designation system has been discontinued but is still widely used. The AISI type designation for a grade consisted of the letter M followed by a number. The letter M stood for magnetic material, and the number was approximately equal to 10 times the maximum permissible core loss in watts per pound for 0.014-in material at 15 kG, 60 Hz in 1947.

Nonoriented electrical steels have approximately the same magnetic properties in all directions in the plane of the material (see Figs. 4-8 and 4-9). The common application is in punched laminations for large

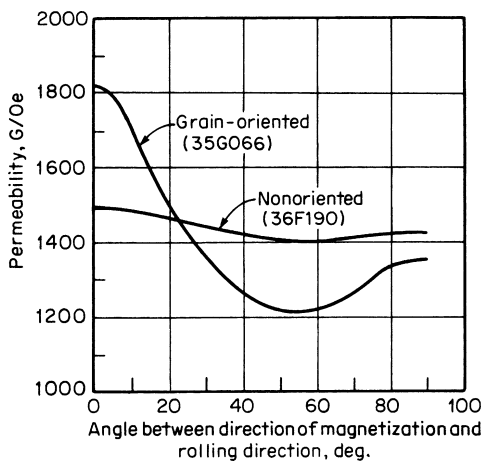


FIGURE 4-8 Effect of direction of magnetization on normal permeability at 10 Oe of fully processed electrical steels.

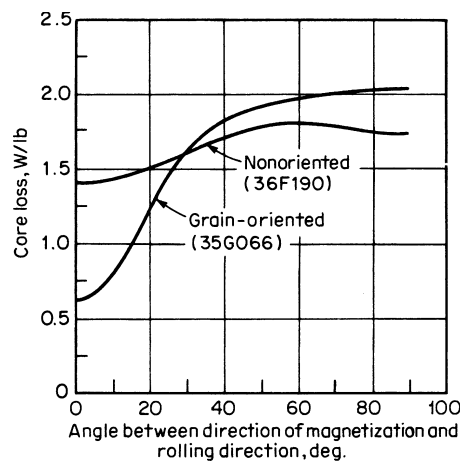


FIGURE 4-9 Effect of direction of magnetization on core loss at 15 kG, 60 Hz of fully processed electrical steel.

and small rotating machines and for small transformers. Today, nonoriented materials are always cold-rolled to final thickness. Hot rolling to final thickness is no longer practiced. Nonoriented materials are available in both fully processed and semiprocessed conditions.

Fully processed nonoriented materials have their magnetic properties completely developed by the producer. Stresses introduced into these materials during fabrication of magnetic cores must be relieved by annealing to achieve optimal magnetic properties in the cores. In many applications, however, the degradation of the magnetic properties during fabrication is slight and/or can be tolerated, and the stress-relief anneal is omitted. Fully processed nonoriented materials contain up to about 3.5% silicon. Additionally, a small amount (about 0.5%) of aluminum is usually present. The common thicknesses are 0.014, 0.0185, and 0.025 in.

Semiprocessed nonoriented materials do not have their inherent magnetic properties completely developed by the producer and must be annealed properly to achieve both decarburization and grain growth. These materials are used primarily in high-volume production of small laminations and cores which would require stress-relief annealing if made from fully processed material. Semiprocessed nonoriented materials contain up to about 3% silicon. Additionally, a small amount (about 0.5%) of aluminum is usually present. The carbon content may be as high as 0.05% but should be reduced to 0.005% or less by the required anneal. The common thicknesses of semiprocessed nonoriented materials are 0.0185 and 0.025 in.

Grain-oriented electrical steels have a pronounced directionality in their magnetic properties (Figs. 4-8 and 4-9). This directionality is a result of the “cube-on-edge” crystal structure achieved by proper composition and processing. Grain-oriented materials are employed most effectively in magnetic cores in which the flux path lies entirely or predominantly in the rolling direction of the material. The common application is in cores of power and distribution transformers for electric utilities.

Grain-oriented materials are produced in a fully processed condition, either unflattened or thermally flattened, in thicknesses of 0.0090, 0.0106, 0.0118, and 0.0138 in. Unflattened material has appreciable coil set or curvature. It is used principally in making spirally wound or formed cores. These cores must be stress-relief annealed to relieve fabrication stresses. Thermally flattened material is employed principally in making sheared or stamped laminations. Annealing of the laminations to remove both residual stresses from the thermal-flattening and fabrication stresses is usually recommended. However, special thermally flattened materials are available which do not require annealing when used in the form of wide flat laminations.

Two types of grain-oriented electrical steels are currently being produced commercially. The regular type, which was introduced many years ago, contains about 3.15% silicon and has grains about 3 mm in diameter. The high-permeability type, which was introduced more recently, contains about 2.9% silicon and has grains about 8 mm in diameter. In comparison with the regular type, the high-permeability type has better core loss and permeability at high inductions.

Some characteristics and applications for electrical steels are shown in Table 4-4.

Surface insulation of the surfaces of electrical steels is needed to limit the interlaminar core losses of magnetic cores made of electrical steels. Numerous surface insulations have been developed to meet the requirements of various applications. The various types of surface insulations have been classified by AISI.

Annealing of laminations or cores made from electrical steels is performed to accomplish either stress relief in fully processed material or decarburization and grain growth in semiprocessed material. Both batch-type annealing furnaces and continuous annealing furnaces are employed. The former is best suited for low-volume or varied production, while the latter is best suited for high-volume production.

Stress-relief annealing is performed at a soak temperature in the range from 730 to 845°C. The soak time need be no longer than that required for the charge to reach soak temperature. The heating and cooling rates must be slow enough so that excessive thermal gradients in the material are avoided. The annealing atmosphere and other annealing conditions must be such that chemical contamination of the material is avoided.

Annealing for decarburization and grain growth is performed at a soak temperature in the range from 760 to 870°C. Atmospheres of hydrogen or partially combusted natural gas and containing water vapor are often used. The soak time required for decarburization depends not only on the

TABLE 4-4 Some Characteristics and Typical Applications for Specific Types of Electrical Steels

ASTM type	Some characteristics	Typical applications
Oriented types		
23G048 through 35G066 or 27H076 through 35H094 or 27P066 through 35P076	Highly directional magnetic properties due to grain orientation. Very low core loss and high permeability in rolling direction.	Highest-efficiency power and distribution transformers with lower weight per kVA. Large generators and power transformers.
Nonoriented types		
36F145 and 47F168	Lowest core loss, conventional grades. Excellent permeability at low inductions.	Small power transformers and rotating machines of high efficiency.
36F158 through 64F225 or 47S178 and 64S194	Low core loss, good permeability at low and intermediate inductions.	High-reactance cores, generators, stators of high-efficiency rotating equipment.
36F190 through 64F270 or 47S188 through 64S260	Good core loss, good permeability at all inductions, and low exciting current. Good stamping properties.	Small generators, high-efficiency, continuous duty rotating ac and dc machines.
47F290 through 64F600 or 47S250 through 64S350	Ductile, good stamping properties, good permeability at high inductions.	Small motors, ballasts, and relays.

temperature and atmosphere but also on the dimensions of the laminations or cores being annealed. If the dimensions are large, long soak times may be required.

Magnetic lamination steels are cold-rolled low-carbon steels intended for magnetic applications, primarily at power frequencies. The magnetic properties of magnetic lamination steels are not normally guaranteed and are generally inferior to those of electric steels. However, magnetic lamination steels are frequently used as core materials in small electrical devices, especially when the cost of the core material is a more important consideration than the magnetic performance.

Usually, but not always, stamped laminations or assembled core structures made from magnetic lamination steels are given a decarburizing anneal to enhance the magnetic properties. Optimal magnetic properties are obtained when the carbon content is reduced to 0.005% or less from its initial value, which may approach 0.1%. The soak temperature of the anneal is in the range from 730 to 790°C. The atmosphere most often used at the present time is partially combusted natural gas with a suitable dew point. Soak time depends to a considerable degree on the dimensions of the laminations or core structures being annealed.

Three types of magnetic lamination steels are produced. Type 1 is usually made to a controlled chemical composition and is furnished in the full-hard or annealed condition without guaranteed magnetic properties. Type 2 is made to a controlled chemical composition, given special processing, and furnished in the annealed condition without guaranteed magnetic properties. After a suitable anneal, the magnetic properties of Type 2 are superior to those of Type 1. Type 2S is similar to Type 2, but the core loss is guaranteed.

4.2.8 Materials for Special Purposes

For certain applications of soft or nonretentive materials, special alloys and other materials have been developed, which, after proper fabrication and heat treatment, have superior properties in certain ranges of magnetization. Several of these alloys and materials will be described.

Nickel-Iron Alloys. Nickel alloyed with iron in various proportions produces a series of alloys with a wide range of magnetic properties. With 30% nickel, the alloy is practically nonmagnetic and has a resistivity of 86 $\mu\Omega/\text{cm}$. With 78% nickel, the alloy, properly heat-treated, has very high permeability. These effects are shown in Figs. 4-10 and 4-11. Many variations of this series have been

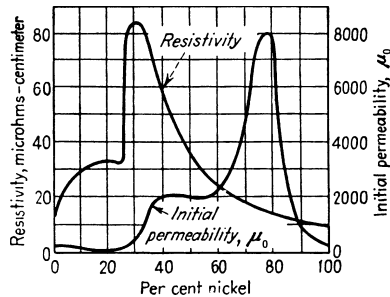


FIGURE 4-10 Electrical resistivity and initial permeability of iron-nickel alloys with various nickel contents.

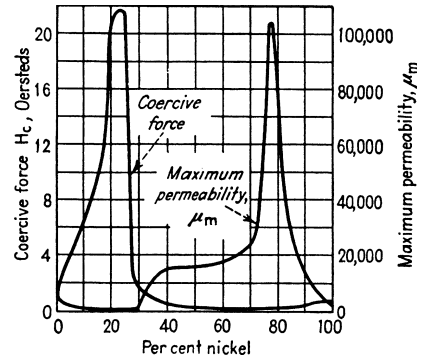


FIGURE 4-11 Maximum permeability and coercive force of iron-nickel alloys with various nickel contents.

developed for special purposes. Table 4-5 lists some of the more important commercial types of nickel-iron alloys, with their approximate properties. These alloys are all very sensitive to heat treatment, so their properties are largely influenced thereby.

Permalloy. This is a term applied to a number of nickel-iron alloys developed by the Bell Laboratories, each specified by a prefix number indicating the nickel content. The term is usually associated with the 78.5% nickel-iron alloys, the important properties of which are high permeability and low hysteresis loss in relatively low magnetizing fields. These properties are obtained by a unique heat treatment consisting of a high-temperature anneal, preferably in hydrogen, with slow cooling followed by rapid cooling from about 625°C. The alloy is very sensitive to mechanical strain, so it is desirable to heat-treat the alloy in its final form. The addition of 3.8% chromium or molybdenum increases the resistivity from 16 to 65 and 55 $\mu\Omega \cdot \text{cm}$, respectively, without seriously impairing the magnetic quality. In fact, low-density permeabilities are better with these additions. These alloys have found their principal application as a material for the continuous loading of submarine cables and in loading coils for landlines.

By special long-time high temperature treatments, maximum permeability values greater than 1 million have been obtained. The double treatment required by the 78% Permalloy is most effective when the strip is thin, say, under 10 mils. For greater thicknesses, the quick cooling from 625°C is not uniform throughout the section, and loss of quality results.

TABLE 4-5 Special-Purpose Materials

Name	Approximate composition, %	Saturation, G	Maximum permeability	Coercivity (from saturation), Oe	Initial permeability	Resistivity, $\mu\Omega \cdot \text{cm}$
78 Permalloy	78.5 Ni	10,500	70,000	-0.05	8,000	16
MoPermalloy	79 Ni, 4.0 Mo	8,000	90,000	-0.05	20,000	55
Supermalloy	79 Ni, 5 Mo	7,900	900,000	-0.002	100,000	60
48% nickel-iron	48 Ni	16,000	60,000	-0.06	5,000	45
Monimax	47 Ni, 3 Mo	14,500	35,000	-0.10	2,000	80
Sinimax	43 Ni, 3 Si	11,000	35,000	-0.10	3,000	85
Mumetal	77 Ni, 5 Cu, 2 Cr	6,500	85,000	-0.05	20,000	60
Deltamax	50 Ni	15,500	85,000	-0.10		45

A 48% nickel-iron was developed for applications requiring a moderately high-permeability alloy with higher saturation density than 78 Permalloy. The same general composition is marketed under many names, such as Hyperm 50, Hipernik, Audiolloy, Allegheny Electric Metal, 4750, and Carpenter 49 alloy. Annealing is recommended after all mechanical operations are completed. These alloys have found extensive use in radio, radar, instrument, and magnetic-amplifier components.

Deltamax. By the use of special techniques of cold reduction and annealing, the 48% nickel-iron alloy develops directional properties resulting in high permeability and a square hysteresis loop in the rolling direction. A similar product is sold under the name of Orthonic. For optimal properties, these materials are rapidly cooled after a 2-h anneal in pure hydrogen at 1100°C. They are generally used in wound cores of thin tape for applications such as pulse transformers and magnetic amplifiers.

Iron-Nickel-Copper-Chromium. The addition of copper and chromium to high-nickel-iron alloys has the effect of raising the permeability at low flux density. Alloys of this type are marketed under the names of Mumetal, 1040 alloy, and Hymu 80. For optimal properties, they are annealed after cutting and forming for 4 h at 1100°C in pure hydrogen and cooled slowly. Important applications are as magnetic shielding for instruments and electronic equipment and as cores in magnetic amplifiers.

Constant-Permeability Alloys. *Constant-permeability alloys* having a moderate permeability which is quite constant over a considerable range of flux densities are desirable for use in circuits in which waveform distortion must be kept at a minimum. Isoperm and Conpernik are two alloys of this type. They are nickel-iron alloys containing 40% to 55% nickel which have been severely cold-worked. Perminvar is the name given to a series of cobalt-nickel-iron alloys (e.g., 50% nickel, 25% cobalt, 25% iron) which also exhibit this characteristic of constant permeability over a low (~800 G) density range. When magnetized to higher flux densities, they give a double loop constricted at the origin so as to give no measurable remanence or coercive force. The characteristics of the alloys in this group vary greatly with the chemical content and the heat treatment. A sample containing approximately 45 Ni, 25 Co, and 30 Fe, baked for 24 h at 425°C and slowly cooled, had hysteresis losses as follows: At 100 G, 214×10^{-4} erg/(cm³)(cycle); at 1003 G, 15.27 ergs; at 1604 G, 163 ergs; at 4950 G, 1736 ergs; and at 13,810 G, 4430 ergs. Over the range of flux densities in which the permeability is constant (from 0 to 600 G), the hysteresis loss is very small, or on the order of the foregoing figure for 100 G. The resistivity of the sample was $19.63 \mu\Omega \cdot \text{cm}$.

Monel. *Monel metal* is an alloy of 67% nickel, 28% copper, and 5% other metals. It is slightly magnetic below 95°C.

Iron-Cobalt Alloys. The addition of cobalt to iron has the effect of raising the saturation intensity of iron up to about 36% cobalt (Fe₂Co). This alloy is useful for pole pieces of electromagnets and for any application where high magnetic intensity is desired. It is workable hot but quite brittle cold. *Hyperco* contains approximately $\frac{1}{3}$ Co, $\frac{2}{3}$ Fe, plus 1% to 2% “added element.” Total core loss is about 2.5 W/lb at 15 kG and 0.010 in thick. It is available as hot-rolled sheet, cold-rolled strip, plates, and forgings. The 50% cobalt-iron alloy Permendur has a high permeability in fields up to 50 Oe and, with about 2% vanadium added, can be cold-rolled.

Iron-Silicon Aluminum Alloys. Aluminum in small percentages, usually under 0.5%, is a valuable addition to the iron-silicon alloy. Its principal function appears to be as a deoxidizer. Masumoto has investigated soft magnetic alloys containing much higher percentages of aluminum and found several that have high permeabilities and low hysteresis losses. Certain compositions have very low magnetostriction and anisotropy, high initial permeability, and high electrical resistivity. An alloy of 9.6% silicon and 6% aluminum with iron has better low-flux-density properties than the Permalloys. However, poor ductility has limited these alloys to dc applications in cast configurations or in insulated pressed-powder cores for high-frequency uses. These alloys are commonly known as Sendust. The material has been prepared in sheet form by special processes.

Temperature-Sensitive Alloys. Inasmuch as the Curie point of metal may be moved up or down the temperature scale by the addition of other elements, it is possible to select alloys which lose their ferromagnetism at almost any desired temperature up to 1115°C, the change point in cobalt. Iron-based alloys are ordinarily used to obtain the highest possible permeability at points below the Curie temperature. Nickel, manganese, chromium, and silicon are the most effective alloy elements for this purpose, and most alloys made for temperature-control applications, such as instruments, reactors, and transformers, use one or more of these. The Carpenter Temperature Compensator 30 is a nickel-copper-iron alloy which loses its magnetism at 55°C and is used for temperature compensation in meters.

Heusler's Alloys. *Heusler's alloys* are ferromagnetic alloys composed of “nonmagnetic” elements. Copper, manganese, and aluminum are frequently used as the alloying elements. The saturation induction is about one-third that of pure iron.

4.2.9 High-Frequency Materials Applications

Magnetic materials used in reactors, transformers, inductors, and switch-mode devices are selected on the basis of magnetic induction, permeability, and associated material power losses at the design frequency. Control of eddy currents becomes of primary importance to reduce losses and minimize skin effect produced by eddy-current shielding. This is accomplished by the use of high-permeability alloys in the form of wound cores of thin tape, or compressed, insulated powder iron alloy cores, or sintered ferrite cores.

Typically, the thin magnetic strip material is used in applications where operating frequencies range from 400 Hz to 20 kHz. Power conditioning equipment frequently operates at 10 kHz and up, and the magnetic materials used are compressed, powdered iron-alloy cores or sintered ferrite cores. Power losses in magnetic materials are of great concern, especially so when operated at high frequencies.

3% Silicon-Iron Alloys. 3% *Silicon-iron alloys* for high-frequency use are available in an insulated 0.001- to 0.006-in-thick strip that exhibits high effective permeability and low losses at relatively high flux densities. This alloy, as well as other rolled-to-strip soft magnetic alloys, is used to make laminated magnetic cores by various methods, including (1) the wound-core approach for winding toroids and C and E cores, (2) stamped or sheared-to-length laminations for laid-up transformers, and (3) stamped laminations of various configurations (rings E, I, F, L, DU, etc.) for assembly into transformer cores. Laminated core materials usually are annealed after all fabricating and stamping operations have been completed in order to develop the desired magnetic properties of the material. Subsequent forming, bending, or machining may impair the magnetic characteristics developed by the anneal.

Amorphous Metal Alloys. *Amorphous metal alloys* are made using a new technology which produces a thin (0.001 to 0.003 in) ribbon from rapidly quenched molten metal. The alloy solidifies before the atoms have a chance to segregate or crystallize, resulting in a glasslike atomic structure material of high electrical resistivity, 125 to 130 $\mu\Omega \cdot \text{cm}$. A range of magnetic properties may be developed in these materials by using different alloying elements. Amorphous metal alloys may be used in the same high-frequency applications as the cast, rolled-to-strip, silicon-iron, and nickel-iron alloys.

Nickel-Iron Powder Cores. *Nickel-iron powder cores* are made of insulated alloy powder, which is compressed to shape and heat-treated. The alloy composition most widely used is 2-81 Permalloy powder composed of 2% molybdenum, 81% nickel, and balance iron. Another less widely used powder, Sendust, is made of 7% to 13% silicon, 4% to 7% aluminum, and balance iron. Prior to pressing, the powder particles are thinly coated with an inorganic, high-temperature insulation which can withstand the high compacting pressures and the high-temperature (650°C) hydrogen atmosphere anneal. The insulation of the particles lowers eddy-current loss and provides a distributed air gap which can be controlled to provide cores in a range of permeabilities. The 2-81 Permalloy cores

are commercially available in permeability ranges of 14 to 300, and Sendust cores have permeabilities ranging from 10 to 140.

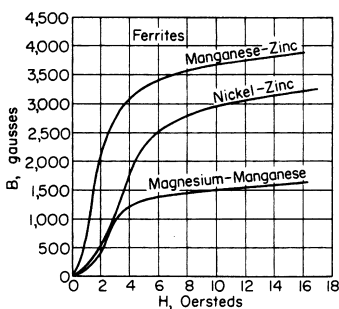
These types of nickel-iron powder cores find use in applications where inductance must remain relatively constant when the magnetic component experiences changes in dc current or temperature. Additional stability over temperature can also be achieved by the addition of low-Curie-temperature powder materials to neutralize the naturally positive permeability-temperature coefficient of the alloy powder. Some applications are in telephone loading coils or filter chokes for power conditioning equipment where output voltage ripple must be minimized. Other uses are for pulse transformers and switch-mode power supplies where low power losses are desired. Operating frequencies can range from 1.0 kHz for 300 permeability materials to 500 kHz for the 14 permeability materials.

Powdered-Iron Cores. Powdered-iron cores are manufactured from various types of iron powders whose particle sizes range from 2 to 100 μm . The particles are electrically insulated from one another using special insulating materials. The insulated powder is blended with phenolic or epoxy binders and a mold-release agent. The powder is then dry-pressed in a variety of shapes including toroids, E cores, threaded tuning cores, cups, sleeves, slugs, bobbins, and other special shapes. A low-temperature bake of the pressed product produces a solid component in which the insulated particles provide a built-in air gap, reducing eddy-current losses, increasing electrical Q , and thus allowing higher operating frequencies. The use of different iron powder blends and insulation systems provides a range of permeability, from 4 to 90, for use over the frequency spectrum of 50 Hz to 250 MHz. Applications include high-frequency transformers, tuning coils, variable inductors, rf chokes, and noise suppressors for power supply and power control circuits.

Ferrite Cores. Ferrite cores are molded from a mixture of metallic oxide powders such that certain iron atoms in the cubic crystal of magnetite (ferrous ferrite) are replaced by other metal atoms, such as Mn and Zn, to form manganese zinc ferrite, or by Ni and Zn to form nickel zinc ferrite.

Manganese zinc ferrite is the material most commercially available and is used in devices operating below 1.5 MHz. Nickel zinc ferrites are used mainly for filter applications above that frequency. They resemble ceramic materials in production processes and physical properties. The electrical resistivities correspond to those of semiconductors, being at least 1 million times those of metals. Magnetic permeability μ_0 may be as high as 10,000. The Curie point is quite low, however, in the range 100 to 300°C. Saturation flux density is generally below 5000 G (Fig. 4-12). Ferrite materials are available in several compositions which, through processing, can improve one or two magnetic parameters (magnetic induction, permeability, low hysteresis loss, Curie temperature) at the expense of the other parameters. The materials are fabricated into shapes such as toroids; E, U, and I cores; beads; and self-shielding pot cores. Ferrite cores find use in filter applications up to 1.0 MHz, high-frequency power transformers operating at 10 to 100 kHz, pulse transformer delay lines, adjustable-air-gap inductors, recording heads, and filters used in high-frequency electronic circuits.

FIGURE 4-12 Typical normal-induction curves for soft ferrites.



Permanent-Magnet Materials. Permanent-magnet materials that are commercially available may be grouped into five classes as follows:

1. Quench-hardened alloys
2. Precipitation-hardened cast alloys
3. Ceramic materials
4. Powder compacts and elongated single-domain materials
5. Ductile alloys

4.2.10 Quench-Hardened Alloys

Early permanent magnets were made of low-carbon steel (1% C) that was hardened by heat treatment. Later developments saw improvements in the magnetic properties through the use of alloying elements of tungsten, chromium, and cobalt. The chrome steels are less expensive than the cobalt steels, and both find use in hysteresis clutch and motor applications.

Ceramic Magnet Material. *Ceramic magnet material* usage is increasing yearly because of improved magnetic properties and the high cost of cobalt used in metallic alloy magnets. The basic raw material used in these magnets is iron oxide in combination with either strontium carbonate or barium carbonate. The iron oxide and carbonate mixture is calcined, and then the aggregate is ball-milled to a particle size of about 1.0 μm . The material is compacted in dies using the dry powder or a water-based slurry of the powder. High pressures are needed to press the parts to shape. In some ceramic grades, a magnetic field is applied during pressing to orient the material in order to obtain a preferred magnetic orientation. Parts are sintered at high temperatures and ground to finished size using diamond grinding wheels with suitable coolants. Ceramic magnets are hard and brittle, exhibit high electrical resistivities, and have lower densities than cast magnet alloys.

Made in the form of rings, blocks, and arcs, ceramic magnets find use in applications for loud-speakers, dc motors, microwave oven magnetron tubes, traveling wave tubes, holding magnets, chip collectors, and magnetic separator units. Ceramic magnet arcs find wide use in the auto industry in engine coolant pumps, heating-cooling fan motors, and window lift motors. As with other magnets, they are normally supplied nonmagnetized and are magnetized in the end-use structure using magnetizing fields of the order of 10,000 Oe to saturate the magnet. The brittleness of the material necessitates proper design of the magnet support structure so as not to impart mechanical stress to the magnet.

Rare Earth Cobalt Magnets. *Rare earth cobalt magnets* have the highest energy product and coercivity of any commercially available magnetic material. Magnets are produced by powder metallurgy techniques from alloys of cobalt (65% to 77%), rare earth metals (23% to 35%), and sometimes copper and iron. The rare earth metal used is usually samarium, but other metals used are praseodymium, cerium, yttrium, neodymium, lanthanum, and a rare earth metal mixture called *misch metal*. The rare earth alloy is ground to a fine particle size (1 to 10 μm), and the powder is then die-compacted in a strong magnetic field. The part is then sintered and abrasive-ground to finish tolerances.

Although this material uses comparatively expensive raw materials, the high value of coercive force (5500 to 9500 Oe) leads to small magnet size and good temperature stability. These magnets find use in miniature electronic devices such as motors, printers, electron beam focusing assemblies, magnetic bearings, and traveling wave tubes. Plastic-bonded rare earth magnets are also being made, but the magnetic value of the energy product is only a fraction of the sintered product.

Ductile Alloys. *Ductile alloys* include the materials Cunife, Vicalloy, Remalloy, chromium-cobalt-iron (Cr-Co-Fe), and in a limited sense, manganese-aluminum-carbon (Mn-Al-C). They are sufficiently ductile and malleable to be drawn, forged, or rolled into wire or strip forms. A final heat treatment after forming develops the magnetic properties. Cunife has a directional magnetism developed as a result of cold working and finds wide use in meters and automotive speedometers. Vicalloy has been used as a high-quality and high-performance magnetic recording tape and in hysteresis clutch applications. Remalloy has been used extensively in telephone receivers but is now being replaced by a newer, less costly magnetic material.

New permanent-magnet materials that are now being produced are the Cr-Co-Fe alloy and the Mn-Al-C alloy. The Cr-Co-Fe alloy family contains 20% to 35% chromium and from 5% to 25% cobalt. This alloy is unique among permanent-magnet alloys due to its good hot and cold ductility, machinability, and excellent magnetic properties. The heat treatment of the alloy involves a rapid cooling from approximately 1200°C to a spinoidal decomposition phase occurring at about 600°C. The magnetic phase developed in the spinoidal decomposition process may be oriented by a heat treatment in a magnetic field, or the material may be magnetically oriented by “deformation aging” as would be accomplished in a wire-drawing operation. The magnetic properties that can be developed are comparable with those of Alnico 5 and are superior to those of the other ductile alloys,

TABLE 4-6 Comparison of Magnetic and Physical Properties of Selected Commercial Materials

	Alnico 5	Alnico 9	Ferrite	Co5R
B_r , G	12800	10500	4100	9500
H_c , Oe	640	1500	2900	6500
$B_d H_d$, Mg · Oe	5.5	9.0	4.0	22.0
Curie point, °C	850	815	470	740
Temperature coefficient, %/°C	0.02	0.02	0.19	0.03
Density, g/cm ³	7.3	7.3	4.9	8.6
Energy/unit weight	0.8	1.2	0.8	2.6

Cunife, Vicalloy, and Remalloy. Western Electric has introduced a Cr-Co-Fe alloy which replaces Remalloy in the production of telephone receiver magnets and at a lower cost due to reduced cobalt.

The Mn-Al-C Alloy. The Mn-Al-C alloy achieves permanent-magnetic properties (B_r , 5500 G; H_c , 2300 Oe; Mg · Oe energy product, 5 Mg · Oe) when mechanical deformation of the alloy takes place at a temperature of about 720°C. Mechanical deformation may be performed by warm extrusion. Magnet size is limited by the amount of deformation needed to develop and orient the magnetic phase in the alloy. The alloying elements are inexpensive, but the tooling and equipment needed in the deformation process is expensive and may be a factor in the economical production of this magnet alloy. Magnets of this alloy would find use in loudspeakers, motor applications, and microwave oven magnetron tubes. The low density, 5.1 g/cm³, is desirable for motors where reduced inertia and weight savings are important. The low Curie temperature, 320°C, limits the use of this alloy to applications where the ambient temperature is less than 125°C.

Permanent-Magnet Design. Permanent-magnet design involves the calculation of magnet area and magnet length to produce a specific magnetic flux density across a known gap, usually with the magnet having the smallest possible volume. Designs are developed from magnet material hysteresis loop data of the second quadrant, commonly called *demagnetization curves*.

Other considerations are the operating temperature of the magnetic assembly, magnet weight, and cost. Also, care should be exercised in the calculation of any steel return path cross section to ensure that it is adequate to carry the flux output of the magnet. Table 4-6 illustrates the range of magnetic characteristics that may be considered in the design. Detailed magnetic and material specifications may be obtained from the magnet manufacturer.

4.3 INSULATING MATERIALS

4.3.1 General Properties

Electrical Insulation and Dielectric Defined. Electrical insulation is a medium or a material which, when placed between conductors at different potentials, permits only a small or negligible current in phase with the applied voltage to flow through it. The term *dielectric* is almost synonymous with electrical insulation, which can be considered the applied dielectric. A perfect dielectric passes no conduction current but only capacitive charging current between conductors. Only a vacuum at low stresses between uncontaminated metal surfaces satisfies this condition.

The range of resistivities of substances which can be considered insulators is from greater than $10^{20} \Omega \cdot \text{cm}$ downward to the vicinity of $10^6 \Omega \cdot \text{cm}$, depending on the application and voltage stress. There is no sharp boundary defined between low-resistance insulators and semiconductors. If the voltage stress is low and there is little concern about the level of current flow (other than that which would heat and destroy the insulation), relatively low-resistance insulation can be tolerated.

Circuit Analogy of a Dielectric or Insulation. Any dielectric or electrical insulation can be considered as equivalent to a combination of capacitors and resistors which will duplicate the current-voltage behavior at a particular frequency or time of voltage application. In the case of some dielectrics, simple linear capacitors and resistors do not adequately represent the behavior. Rather, resistors and capacitors with particular nonlinear voltage-current or voltage-charge relations must be postulated to duplicate the dielectric current-voltage characteristic.

The simplest circuit representation of a dielectric is a parallel capacitor and resistor, as shown in Fig. 4-13 for $R_s = 0$. The perfect dielectric would be simply a capacitor. Another representation of a dielectric is a series-connected capacitor and resistor as in Fig. 4-13 for $R_p = \infty$, while still another involves both R_s and R_p .

The ac dielectric behavior is indicated by the phase diagram (Fig. 4-14). The perfect dielectric capacitor has a current which leads the voltage by 90° , but the imperfect dielectric has a current which leads the voltage by less than 90° . The dielectric phase angle is θ , and the difference, $90^\circ - \theta = \delta$, is the loss angle. Most measurements of dielectrics give directly the tangent of the loss angle $\tan \delta$ (known as the *dissipation factor*) and the capacitance C . In Fig. 4-13, if $R_p = \infty$, the series $R_s - C$ has a $\tan \delta = 2\pi f C_s R_s$, and if $R_s = 0$, the parallel $R_p - C$ has a $\tan \delta = 1/2\pi f C R_p$.

The ac power or heat loss in the dielectric is $V^2 2\pi f C \tan \delta$ watts, or $VI \sin \delta$ watts, where $\sin \delta$ is known as the power factor, V is the applied voltage, I is the total current through the dielectric, and f is the frequency. From this it can be seen that the equivalent parallel conductance of the dielectric σ (the inverse of the equivalent parallel resistance ρ) is $2\pi f C \tan \delta$. The ac conductivity is

$$\sigma = (5/9) f \epsilon' \tan \delta \times 10^{-12} \Omega^{-1} \text{ cm}^{-1} = 1/\rho \quad (4-54)$$

where ϵ' is the permittivity (or relative dielectric constant) and f is the frequency. (The IEEE now recommends the symbol ϵ' for the dielectric constant relative to a vacuum. The literature on dielectrics and insulation also has used κ [kappa] for this dimensionless quantity or ϵ'_r . In some places, ϵ' has been used to indicate the absolute dielectric constant, which is the product of the relative dielectric constant and the dielectric constant of a vacuum ϵ_0 , which is equal to 8.85×10^{-12} F/m.) κ_0 also has been used to represent the dielectric constant of a vacuum. While the ac conductivity theoretically increases in proportion to the frequency, in practice, it will depart from this proportionality insofar as ϵ' and $\tan \delta$ change with frequency.

Capacitance and Permittivity or Dielectric Constant. The capacitance between plane electrodes in a vacuum (with fringing neglected) is

$$C = \epsilon' \epsilon_0 A/t = 0.0884 \times 10^{-12} A/t \quad \text{farads} \quad (4-55)$$

where ϵ_0 is the dielectric constant of a vacuum, A is the area in square centimeters, and t is the spacing of the plates in centimeters. ϵ_0 is 0.225×10^{-12} F/in when A and t are expressed in inch units.

When a dielectric material fills the volume between the electrodes, the capacitance is higher by virtue of the charges within the molecules and atoms of the material, which attract more charge to

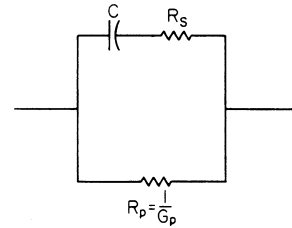


FIGURE 4-13 Equivalent circuit of a dielectric.

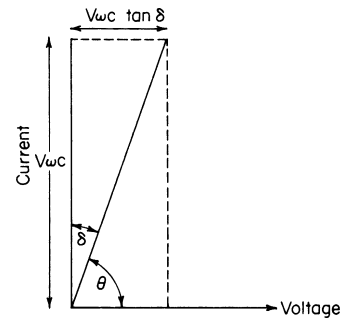


FIGURE 4-14 Current-voltage phase relation in a dielectric.

the capacitor planes for the same applied voltage. The capacitance with the dielectric between the electrodes is

$$C = \epsilon' \epsilon_0 A/t \quad (4-56)$$

where ϵ' is the relative dielectric constant of the material. The capacitance relations for several other commonly occurring situations are

Coaxial conductors:
$$C = \frac{2\pi\epsilon'\epsilon_0 L}{\ln(r_2/r_1)} \quad \text{farads} \quad (4-57)$$

Concentric spheres:
$$C = \frac{4\pi\epsilon'\epsilon_0 r_1 r_2}{r_2 - r_1} \quad \text{farads} \quad (4-58)$$

Parallel cylindrical conductors:
$$C = \frac{2\pi\epsilon'\epsilon_0 L}{\cosh^{-1}(D/2r)} \quad \text{farads} \quad (4-59)$$

In these equations, L is the length of the conductors, r_2 and r_1 are the outer and inner radii, and D is the separation between centers of the parallel conductors with radii r . For dimensions in centimeters, ϵ_0 is 0.0884 F/cm.

The value of ϵ' depends on the number of atoms or molecules per unit volume and the ability of each to be polarized (i.e., to have a net displacement of their charge in the direction of the applied voltage stress). Values of ϵ' range from unity for vacuum to slightly greater than unity for gases at atmospheric pressure, 2 to 8 for common insulating solids and liquids, 35 for ethyl alcohol and 91 for pure water, and 1000 to 10,000 for titanate ceramics (see Table 4-7 for typical values).

The relative dielectric constant of materials is not constant with temperature, frequency, and many other conditions and is more appropriately called the *dielectric permittivity*. Refer to the volume by Smyth (1955) for a discussion of the relation of ϵ' to molecular structure and to von Hippel (1954) and other tables of dielectric materials from the MIT Laboratory for Insulation Research. The permittivity of many liquids has been tabulated in *NBS Circ.* 514. The *Handbook of Chemistry and Physics* (Chemical Rubber Publishing Co.) also lists values for a number of plastics and other materials.

The permittivity of many plastics, ceramics, and glasses varies with the composition, which is frequently variable in nominally identical materials. In the case of some plastics, it varies with degree of cure and in the case of ceramics with the firing conditions. Plasticizers often have a profound effect in raising the permittivity of plastic compositions.

There is a force of attraction between the plates of a capacitor having an applied voltage. The stored energy is $\frac{1}{2} CV^2$ J. The force equals the derivative of this energy with respect to the plate separation: $(\frac{1}{2}) \epsilon' \epsilon_0 E^2 \times 10^2 \text{ N/cm}^2$ or $(\frac{1}{2}) \epsilon' \epsilon_0 E^2 \times 10 \text{ bar}$, where E is the electric field in volts per centimeter. The force increases proportionally to the capacitance or permittivity. This leads to a force of attraction of dielectrics into an electric field, that is, a net force which tends to move them toward a region of high field. If two dielectrics are present, the one with higher permittivity will displace the one with lower permittivity in the higher-field region. For example, air bubbles in a liquid are repelled from high-field regions. Correspondingly, elongated dielectric bodies are rotated into the direction of the electric field. In general, if the voltage on a dielectric system is maintained constant, the dielectrics move (if they are able) to create a higher capacitance.

Resistance and Resistivity of Dielectrics and Insulation. The measured resistance R of insulation depends on the geometry of the specimen or system measured, which for a parallel-plate arrangement is

$$R = \rho t/A \quad \text{ohms} \quad (4-60)$$

where t is the insulation thickness in centimeters, A is the area in square centimeters, and ρ is the dielectric resistivity in ohm-centimeters. If t and A vary from place to place, the effective "insulation resistance" will be determined by the effective integral of the t/A ratio over all the area under stress, on the assumption that the material resistivity ρ does not change. If the material is not homogeneous and materials of different resistivities appear in parallel, the system can be treated as parallel

TABLE 4-7 Dielectric Permittivity (Relative Dielectric Constant), ϵ'

	k		k
Inorganic crystalline		Polymer resins	
NaCl, dry crystal	5.5	Nonpolar resins	
CaCO ₂ (av)	9.15	Polyethylene	2.3
Al ₂ O ₃	10.0	Polystyrene	2.5–2.6
MgO	8.2	Polypropylene	2.2
BN	4.15	Polytetrafluoroethylene	2.0
TiO ₂ (av)	100	Polar resins	
BaTiO ₂ crystal	4,100	Polyvinyl chloride (rigid)	3.2–3.6
Muscovite mica	7.0–7.3	Polyvinyl acetate	3.2
Fluorophlogopite (synthetic mica)	6.3	Polyvinyl fluoride	8.5
Ceramics		Nylon	4.0–4.6
Alumina	8.1–9.5	Polyethylene terephthalate	3.25
Steatite	5.5–7.0	Cellulose cotton fiber (dry)	5.4
Forsterite	6.2–6.3	Cellulose Kraft fiber (dry)	5.9
Aluminum silicate	4.8	Cellulose cellophane (dry)	6.6
Typical high-tension porcelain	6.0–8.0	Cellulose triacetate	4.7
Titanates	50–10,000	Tricynoethyl cellulose	15.2
Beryl	4.5	Epoxy resins unfilled	3.0–4.5
Zirconia	8.0–10.5	Methylmethacrylate	3.6
Magnesia	8.2	Polyvinyl acetate	3.7–3.8
Glass-bonded mica	6.4–9.2	Polycarbonate	2.9–3.0
Glasses		Phenolics (cellulose-filled)	4–15
Fused silica	3.8	Phenolica (glass-filled)	5–7
Corning 7740 (common laboratory Pyrex)	5.1	Phenolics (mica-filled)	4.7–7.5
		Silicones (glass-filled)	3.1–4.5

resistors: $R = R_a R_b / (R_a + R_b)$. In this case, the lower-resistivity material usually controls the overall behavior. But if materials of different resistivities appear in series in the electric field, the higher-resistivity material generally will control the current, and a majority of the voltage will appear across it, as in the case of series resistors.

The resistance of dielectrics and insulation is usually time-dependent and (for the same reason) frequency-dependent. The dc behavior of dielectrics under stress is an extension of the low-frequency behavior. The ac and dc resistance and permittivity can, in principle, be related for comparable times and frequencies.

Current flow in dielectrics can be divided into parts: (a) the true dc current, which is constant with time and would flow indefinitely, is associated with a transport of charge from one electrode into the dielectric, through the dielectric, and out into the other electrode, and (b) the polarization or absorption current, which involves, not charge flow through the interface between the dielectric and the electrode, but rather the displacement of charge within the dielectric. This is illustrated in Fig. 4-15, where it is shown that the displaced or absorbed charge is responsible for a reverse current when the voltage is removed.

Polarization current results from any of the various forms of limited charge displacement which can occur in the dielectric. The displacement occurring first (within less than nanoseconds) is the electronic and intramolecular charged atom displacement responsible for the very high frequency permittivity.

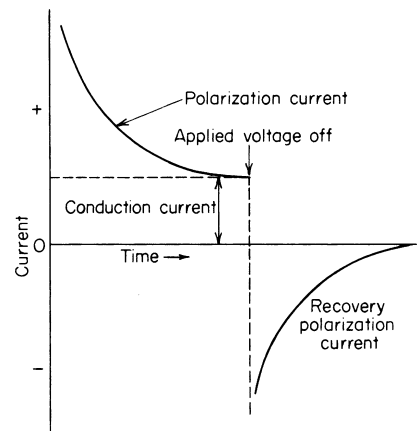


FIGURE 4-15 Typical dc dielectric current behavior.

The next slower displacement is the rotation of dipolar molecules and groups which are relatively free to move. The displacement most commonly observed in dc measurements, that is, currents changing in times of the order of seconds and minutes, is due to the very slow rotation of dipolar molecules and ions moving up to internal barriers in the material or at the conductor surfaces. When those slower displacement polarizations occur, the dielectric constant declines with increasing frequency and approaches the square of the optical refractive index η^2 at optical frequencies.

In composite dielectrics (material with relatively lower resistance intermingled with a material of relatively higher resistance), a large interfacial or Maxwell-Wagner type of polarization can occur. A circuit model of such a situation can be represented by placing two of the circuits of Fig. 4-13 in series and making the parallel resistance of one much lower than the other. To get the effect, it is necessary that the time constant $R_p C$ be different for each material.

A simple model of the polarization current predicts an exponential decline of the current with time: $I_p = Ae^{-\alpha t}$, similar to the charging of a capacitor through a resistor. Composite materials are likely to have many different time constants, $\alpha = 1/RC$, superimposed. It is found empirically that the polarization or absorption current decreases inversely as a simple negative exponent of the time

$$I = Ar^{-n} \quad (4-61)$$

The ratio of the current at 1 min to that at 10 min has been called the *polarization index* and is used to indicate the quality of composite machine insulation. A low polarization index associated with a low resistance sometimes indicates parallel current leakage paths through or over the surface of insulation (e.g., in adsorbed water films).

The level of the conduction current which flows essentially continuously through insulation is an indication of the level of the ionic concentration and mobility in the material. Frequently, as with salt in water, the ions are provided by dissolved, absorbed, or included impurity electrolytes in the material rather than by the material itself. Purifying the material will therefore often raise the resistivity. If it is liquid, purification can be done with adsorbent clays or ion-exchange resins.

The conductivity of ions in an insulation is given by the equation

$$\sigma = \mu ec \quad \Omega^{-1} \cdot \text{cm}^{-1} \quad (4-62)$$

where μ is the ion mobility, e is the ionic charge in coulombs, and c is the ionic concentration per cubic centimeter. The mobility, expressed in centimeters per second-volt per centimeter, decreases inversely with the effective internal viscosity and is very low for hard resins, but it increases with temperature and with softness of the resin or fluidity of liquids. The ionic conductivity also varies widely with material purity. Among the polymers and resins, nonpolar resins such as polyethylene are likely to have high resistivities, on the order of 10^{16} or greater, since they do not readily dissolve or dissociate ionic impurities. Harder or crystalline polar resins have higher resistivity than do similar softer resins of similar dielectric constant and purity. Resins and liquids of higher dielectric constant usually have higher conductivities because they dissolve ionic impurities better, and the impurities dissociate to ions much more readily in a higher dielectric constant medium. Ceramics and glasses have lower resistivity if they contain alkali ions (sodium and potassium), since these ions are highly mobile.

Water is particularly effective in decreasing the resistivity by increasing the ionic concentration and mobility of materials, on the surface as well as internally. Water associates with impurity ions or ionizable constituents within or on the surface or interfaces. It helps to dissociate the ions by virtue of its high dielectric constant and provides a local environment of greater mobility, particularly as surface water films.

The ionic conductivity σ , exclusive of polarization effects, can be expected to increase exponentially with temperature according to the relation

$$\sigma = \sigma_0 e^{-B/T} \quad (4-63)$$

where T is the Kelvin temperature and σ_0 and B are constants. This relation, $\log \sigma$ versus $1/T$, is shown in Fig. 4-16. It is often observed that at lower temperatures, where the resistivity is higher, the resistivity tends to be lower than the extrapolated higher temperature line would predict. There are at least two possible reasons for this: the effect of adsorbed moisture and the contribution of a very slowly decaying polarization current.

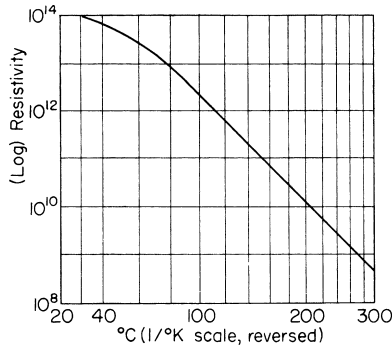


FIGURE 4-16 Typical dielectric resistivity-temperature dependence. (Corning.)

Variation of Dielectric Properties with Frequency.

The permittivity of dielectrics invariably tends downward with increasing frequency, owing to the inability of the polarizing charges to move with sufficient speed to follow the increasing rate of alternations of the electric field. This is indicated in Fig. 4-17. The sharper decline in permittivity is known as a *dispersion region*. At the lower frequencies, the ionic-interface polarization declines first; next, the molecular dipolar polarizations decline. With some polar polymers, two or more dipolar dispersion regions may occur owing to different parts of the molecular rotation.

Figure 4-17 is typical of polymers and liquids but not of glasses and ceramics. Glasses, ceramics, and inorganic crystals usually have much flatter permittivity-frequency curves, similar to that shown for the nonpolar polymer, but at a higher level, owing to their atom-ion

displacement polarization, which can follow the electric field usually up to infrared frequencies.

The dissipation factor-frequency curve indicates the effect of ionic migration conduction at low frequency. It shows a maximum at a frequency corresponding to the permittivity dispersion region. This maximum is usually associated with a molecular dipolar rotation and occurs when the rotational mobility is such that the molecular rotation can just keep up with frequency of the applied field. Here it has its maximum movement in phase with the voltage, thus contributing to conduction current. At lower frequencies, the molecule dipole can rotate faster than the field and contributes more to permittivity. At higher frequencies it cannot move fast enough. Such a dispersion region can also occur because of ionic migration and interface polarization if the interfaces are closely spaced and if the frequency and mobility have the required values.

The frequency region where the dipolar dispersion occurs depends on the rotational mobility. In mobile, low-viscosity liquids, it is in the 100- to 10,000-MHz range. In viscous liquids, it occurs in the region of 1 to 100 MHz. In soft polymers it may occur in the audio-frequency range, and with hard polymers it is likely to be at very low frequency (indistinguishable from dc properties). Since the viscosity is affected by the temperature, increased temperature shifts the dispersion to higher frequencies.

Variation of Dielectric Properties with Temperature. The trend in ac permittivity and conductivity, as measured by the dissipation factor, is controlled by the increasing ionic migrational and dipolar molecular rotational mobility with increasing temperature. This curve, which is indicated

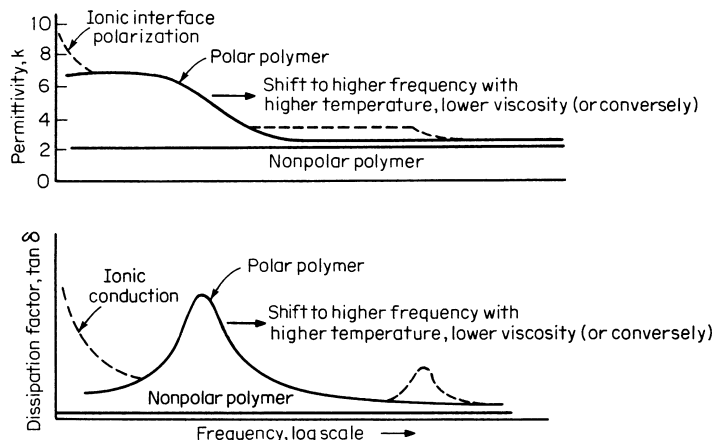


FIGURE 4-17 Typical variation in dielectric properties with frequency.

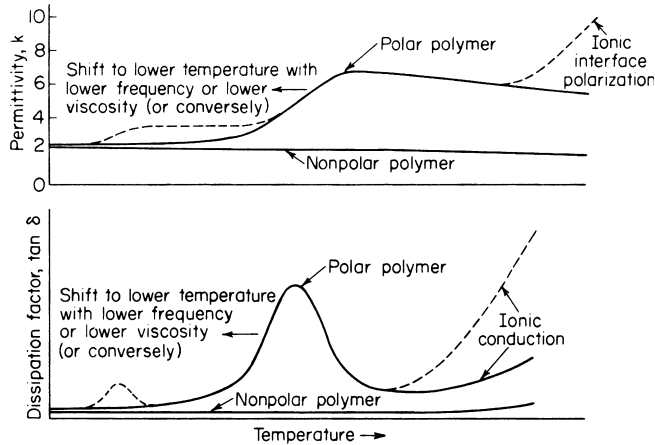


FIGURE 4-18 Typical variation in dielectric properties with temperature.

in Fig. 4-18, is in most respects a mirror image of the frequency trend shown in Fig. 4-17, since the two effects are interrelated.

The permittivity-dispersion and dissipation factor maximum region occurs below room temperature for viscous liquids and still lower for mobile liquids. In fact, mobile liquids may crystallize before they would show dispersion, except at high frequencies. With polymers, the dissipation factor maxima is likely to occur, at power frequencies, at a temperature close to a softening-point or internal second-order transition-point temperature. Dielectric dispersion and mechanical modulus dispersion usually can be correlated at the same temperature for comparable frequencies.

Composite Dielectrics. The dielectric properties of composite dielectrics are generally a weighted average of the individual component properties, unless there is interaction, such as dissolving (as opposed to intermixing) of one material in another, or chemical reaction of one with another. Interfaces created by the mixing present a special factor, which often can lead to a higher dissipation factor and lower resistivity as a result of moisture and/or impurity concentration at the interface.

The ac properties of sheets of two dielectrics of dielectric constant k_1 and k_2 and of thickness t_1 and t_2 placed in series are related to the properties of the individual materials by the series of capacitance and impedance relation

$$C = \frac{k_0 k_1 k_2 A}{k_1 t_2 + k_2 t_1} \quad (4-64)$$

$$\tan \delta = \frac{(t_1/t_2)\epsilon'_2 \tan \delta_1 + \epsilon'_1 \tan \delta_2}{\epsilon'_1 + \epsilon'_2(t_1/t_2)} \quad (4-65)$$

Similarly, the properties of two dielectrics in parallel are

$$C = \epsilon_0 \left(\frac{\epsilon'_1 A_1}{t_1} + \frac{\epsilon'_2 A_2}{t_2} \right) \quad (4-66)$$

$$\tan \delta = \frac{t_2 \epsilon'_1 A_1 \tan \delta_1 + t_1 \epsilon'_2 A_2 \tan \delta_2}{t_2 \epsilon'_1 A_1 + t_1 \epsilon'_2 A_2} \quad (4-67)$$

With steady dc voltages, the resistivities control the current. With equal-area layer dielectrics in series,

$$R = R_1 + R_2 = \frac{1}{A} (\rho_1 t_1 + \rho_2 t_2) \quad (4-68)$$

When the dielectrics are in parallel and of equal thickness t ,

$$R = \frac{R_1 R_2}{R_1 + R_2} = \frac{\rho_1 \rho_2 t}{\rho_1 A_2 + \rho_2 A_1} \quad (4-69)$$

Potential Distribution in Dielectrics. The maximum potential gradient in dielectrics is of critical significance insofar as the breakdown is concerned, since breakdown or corona is usually initiated at the region of highest gradient. In a uniform-field arrangement of conductors or electrodes, the maximum gradient is simply the applied voltage divided by the minimum spacing. In divergent fields, the gradient must be obtained by calculation (which is possible for some simple arrangements) or by field mapping.

A common situation is the coaxial geometry with inner and outer radii R_1 and R_2 . The gradient at radius r (centimeters) with voltage V applied is given by the equation

$$E = \frac{V}{r \ln (R_2/R_1)} \quad \text{V/cm} \quad (4-70)$$

The gradient is a maximum at $r = R_1$.

When different dielectrics appear in series, the greater stress with ac fields is on the material having the lower dielectric constant. This material will frequently break down first unless its dielectric strength is much higher

$$\frac{E_1}{E_2} = \frac{\epsilon'_2}{\epsilon'_1} \quad \text{and} \quad E_1 = \frac{V}{t_1 + t_2 \epsilon'_1 / \epsilon'_2} \quad (4-71)$$

The effect of the insulation thickness and dielectric constant (as well as the sharpness of the conductor edge) to create sufficient electric stress for local air breakdown (partial discharges) is shown in Fig. 4-19. With dc fields, the stress distributes according to the resistivities of the materials, the higher stress being on the higher-resistivity material.

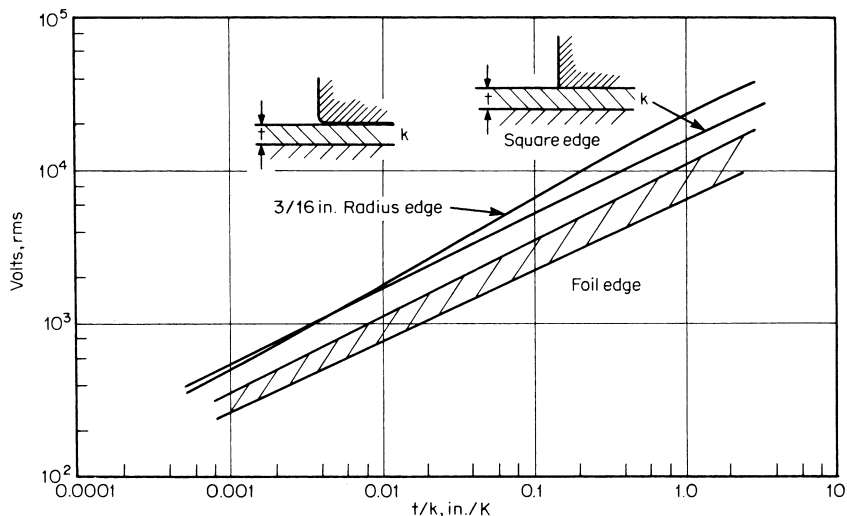


FIGURE 4-19 Corona threshold voltage at conductor edges in air as a function of insulation thickness.

Dielectric Strength. This is defined by the ASA as the maximum potential gradient that the material can withstand without rupture. Practically, the strength is often reported as the breakdown voltage divided by the thickness between electrodes, regardless of electrode stress concentration.

Breakdown appears to require not only sufficient electric stress but also a certain minimum amount of energy. It is a property which varies with many factors such as thickness of the specimen, size and shape of electrodes used in applying stress, form or distribution of the field of electric stress in the material, frequency of the applied voltage, rate and duration of voltage application, fatigue with repeated voltage applications, temperature, moisture content, and possible chemical changes under stress.

The practical dielectric strength is decreased by defects in the material, such as cracks, and included conducting particles and gas cavities. As will be shown in more detail in later sections on gases and liquids, the dielectric strength is quite adversely affected by conducting particles.

To state the dielectric strength correctly, the size and shape of specimen, method of test, temperature, manner of applying voltage, and other attendant conditions should be particularized as definitely as possible.

ASTM standard methods of dielectric strength testing should be used for making comparison tests of materials, but the levels of dielectric strength measured in such tests should not be expected to apply in service for long times. It is best to test an insulation in the same configuration in which it would be used. Also, the possible decline in dielectric strength during long-time exposure to the service environment, thermal aging, and partial discharges (corona), if they exist at the applied service voltage, should be considered. ASTM has thermal life test methods for assessing the long-time endurance of some forms of insulation such as sheet insulation, wire enamel, and others. There are IEEE thermal life tests for some systems such as random wound motor coils.

The dielectric strength varies as the time and manner of voltage application. With unidirectional pulses of voltage, having rise times of less than a few microseconds, there is a time lag of breakdown, which results in an apparent higher strength for very short pulses. In testing sheet insulation in mineral oil, usually a higher strength for pulses of slow rise time and somewhat higher strength for dc voltages is observed.

The trend in breakdown voltage with time is typical of many solid insulation systems.

With ac voltages, the apparent strength declines steadily with time as a result of partial discharges (in the ambient medium at the conductor or electrode edge). These penetrate the solid insulation. The discharges result from breakdown of the gas or liquid prior to the breakdown of the solid. Mica in particular, as well as other inorganic materials, is more resistant to such discharges. Organic resins should be used with caution where the ac voltage gradient is high and partial discharges (corona) may be present. Since the presence of partial discharges on insulation is so important to the long-time voltage endurance, their detection and measurement have become very important quality control and design tools. If discharges continuously strike the insulation within internal cavities or on the surface, the time to failure usually varies inversely as the applied frequency, since the number of discharges per unit time increases almost in direct proportion to the frequency. But in some cases, ambient conditions prevent continuous discharges.

When organic resin insulation is fabricated to avoid partial discharges using conductors or electrodes intimately bonded to the insulation, as in extruded polyethylene cables with a plastic semiconducting interface between the resin and the coaxial inner and outer metal conductors, respectively, the voltage endurance is greatly extended. Imperfections, however, in this "semicon"-resin interface, or at conducting particle inclusions in the resin, can lead to local discharges and the development of "electrical tree" growth. Vacuum impregnating and casting electrodes or conductors into resin also tend to avoid cavities and surface discharges and greatly improve the voltage endurance at high stresses.

The dc strength of solid insulation is usually higher and declines much less with time than the ac strength, since corona discharges are infrequent.

The dielectric strength is much higher where surface discharges are avoided and when the electric field is uniform. This can be achieved with solid materials by recessing spherical cavities into the material and using conducting paint electrodes.

The "intrinsic" electric strength of solid materials measured in uniform fields, avoiding surface discharges, ranges from levels on the order of 0.5 to 1 MV/cm for alkali halide crystals, which are

about the lowest, upward to somewhat more than 10 MV/cm. Polymers and some inorganic materials, such as mica and aluminum oxide, have strengths of 2 to 20 MV/cm for thin films. The strength decreases with increasing thickness and with temperature above a critical temperature (which is usually from 1 to 100°C), below which the strength has a level value or a moderate increase with increasing temperature. Below the critical temperature, the breakdown is believed to be strictly electronic in nature and is constant or increases slightly with temperature. Above this temperature, it declines owing to dielectric thermal heating.

The breakdown voltage of thin insulation materials containing defects, which give the minimum breakdown voltage, declines as the area under stress increases. The effect of area on the strength can be estimated from the standard deviation S of tests on smaller areas by applying minimum value statistics: $V_1 - V_2 = 1.497 S \log(A_1/A_2)$, where V_1 and V_2 are the breakdown voltages of areas A_1 and A_2 .

If the ac or dc conductivity of a dielectric is high or the frequency is high, breakdown can occur as a result of dielectric heating, which raises the temperature of the material sufficiently to cause melting or decomposition, formation of gas, etc. This effect can be detected by measuring the conductivity as a function of applied electric stress. If the conductivity rises with time, with constant voltage, and at constant ambient temperature, this is evidence of an internal dielectric heating. If the heat transfer to the electrodes and ambient surroundings is adequate, the internal temperature eventually may stabilize, but if this heat transfer is inadequate, the temperature will rise until breakdown occurs. The criterion of this sort of breakdown is the heat balance between dielectric heat input and loss to the surroundings.

The dielectric heat input is given by the equation

$$\sigma E^2 = (\epsilon''/\epsilon') f \tan \delta \times 10^{-12} E^2 \quad \text{W/cm}^3 \quad (4-72)$$

where E is the field in volts per centimeter. When this quantity is on the order of 0.1 or greater, dielectric heating can be a problem. It is much more likely to occur with thick insulation and at elevated temperatures.

Water Penetration. Water penetration into electrical insulation also degrades the dielectric strength by several mechanisms. The effect of water to increase the insulation conductivity contributes thereby to a decreased dielectric strength, probably by a thermal breakdown mechanism. Another effect noticed recently, particularly in polyethylene cables, is the development of “water” or “electrochemical trees.” Water (and/or a similar high dielectric constant chemical) can diffuse through polyethylene and collect at tiny hygroscopic inclusion sites, where the water or chemical is adsorbed. Then the electric field causes an expansion and growth of the adsorbed water or chemical in the electric field direction. This may completely bridge the insulation or possibly increase the local electric stress at the site so as to produce an electric tree and eventual breakdown.

Ionizing Radiation. Ionizing radiation, as from nuclear sources, may degrade insulation dielectric strength and integrity by causing polymer chain scission, and cracking of some plastics, as well as gas bubbles in liquids. Also, the conductivity levels in solids and liquids are increased.

Arc Tracking of Insulation. High-current arc discharges between conductors across the surface of organic resin insulation may carbonize the material and produce a conducting track. In the presence of surface water films, formed from rain or condensation, etc., small arc discharges form between interrupted parts of the water film, which is fairly conducting, and conducting tracks grow progressively across the surface, eventually bridging between conductors and causing complete breakdown. Materials vary widely in their resistance to tracking, and there are a variety of dry and wet tests for this property. With proper fillers, some organic resins can be made essentially nontracking. Some resins such as polymethyl methacrylate and polymethylene oxide burst into flame under arcing conditions.

Thermal Aging. Organic resinous insulating materials in particular are subject in varying degrees to deterioration due to thermal aging, which is a chemical process involving decomposition or modification of the material to such an extent that it may no longer function adequately as the intended

insulation. The aging effects are usually accelerated by increased temperature, and this characteristic is used to make accelerated tests to failure or to an extent of deterioration considered dangerous. Such tests are made at appreciably higher than normal operating temperatures, if the expected life is to be several years or more, since useful accelerated tests reasonably should be completed in less than a year.

Frequently, other environmental factors influence the life in addition to the temperature. These include presence or absence of oxygen, moisture, and electrolysis. Mechanical and electrical stress may reduce the life by setting a required level of performance at which the insulation must perform. If this level is high, less deterioration of the insulation is required to reach this level.

Sometimes a complete apparatus is life-tested, as well as smaller specimens involving only one insulation material or a simple combination of these in a simple model. New tests are being devised continually, but there has been some standardization of tests by the IEEE and ASTM and internationally by the IEC.

It is important to note that frequently materials are assigned temperature ratings based on tests of the material alone. Often that material, combined with others in an apparatus or system, will perform satisfactorily at appreciably higher temperatures. Conversely, because of incompatibility with other materials, it may not perform at as high a temperature as it would alone. For this reason, it is considered desirable to make functional operating tests on complete systems. These can also be accelerated at elevated temperatures and environmental exposure conditions such as humidification, vibration, cold-temperature cycling, etc. introduced intermittently. The basis for temperature rating of apparatus and materials is discussed thoroughly in *IEEE Standard Publ. 1*. Tests for determining ratings are described in *IEEE Publs. 98, 99, and 101*.

Application of Electrical Insulation. In applying an insulating material, it is necessary to consider not only the electrical requirements but also the mechanical and environmental conditions of the application. Mechanical failure often leads to electrical failure, and mechanical failure is frequently the primary cause for failure of an aged insulation.

The initial properties of an insulation are frequently more than adequate for the application, but the effects of aging and environment may degrade the insulation rapidly to the point of failure. Thus, the thermal and environmental stability should be considered of equal importance. The effects of moisture and surface dirt contamination should be particularly considered, if these are likely to occur.

4.3.2 Insulating Gases

General Properties of Gases. A gas is a highly compressible dielectric medium, usually of low conductivity and with a dielectric constant only a little greater than unity, except at high pressures. In high electric fields, the gas may become conducting as a result of impact ionization of the gas molecules by electrons accelerated by the field and by secondary processes which produce partial breakdown (corona) or complete breakdown. Conditions which ionize the gas molecules, such as very high temperatures and ionizing radiation (ultraviolet rays, x-rays, gamma rays, high-velocity electrons, and ions such as alpha particles), will also produce some conduction in a gas.

The gas density d (grams per liter) increases with pressure p (torrs or millimeters of mercury) and gram-molecular weight M and decreases inversely with the absolute temperature T (degrees Celsius + 273) according to the relation

$$d = \frac{M}{22.4} \frac{p}{760} \frac{273}{T} \quad \text{g/L} \quad (4-73)$$

The preceding relation is exact for ideal gases but is only approximately correct for most common gases.

If the gas is a vapor in equilibrium with a liquid or solid, the pressure will be the vapor pressure of the liquid or solid. The logarithm of the pressure varies as $-\Delta H/RT$, where ΔH is the heat of vaporization in calories per mole and R is the molar gas constant, 1.98 cal/(mol)(°C). This relation also applies to all common atmospheric gases at low temperatures, below the points where they liquify.

Dielectric Properties at Low Electric Fields

Dielectric Constant. The dielectric constant k of gases is a function of the molecular electrical polarizability and the gas density. It is independent of magnetic and electric fields except when a significant number of ions is present.

Conduction. The conductivity of a pure molecular gas at moderate electric stress and moderate temperature can be assumed, in the absence of any ionizing effect such as ionizing radiation, to be practically zero. Ionizing radiation induces conduction in the gas to a significant extent, depending on the amount absorbed and the volume of gas under stress. The energy of the radiation must exceed, directly or indirectly, the ionization energy of the gas molecules and thus produce an ion pair (usually an electron and positive ion). The threshold ionization energy is on the order of 10 to 25 electronvolts (eV)/molecule for common gases (10.86 eV for methyl alcohol, 12.2 for oxygen, 15.5 for nitrogen, and 24.5 for helium). Only very short wavelength ultraviolet light is effective directly in photoionization, since 10 eV corresponds to a photon of ultraviolet with a wavelength of 1240 Å. Since the photoelectric work function of metal surfaces is much lower (2 to 6 eV; e.g., copper about 4 eV), the longer-wavelength ultraviolet commonly present is effective in ejecting electrons from a negative conductors surface. Such cathode-ejected electrons give the gas apparent conductivity.

High-energy radiation from nuclear disintegration is a common source of ionization in gases. Nuclear sources usually produce gamma rays on the order of 10^6 eV energy. Only a small amount is absorbed in passing through a low-density gas. A flux of 1 R/h produces ion pairs corresponding to a saturation current (segment *ab* of Fig. 4-20) of 0.925×10^{-13} A/cm² of air at 1 atm pressure if all the ions formed are collected at the electrodes. The effect is proportional to the flux and the gas density.

At a voltage stress below about 100 V/cm, some of the ions formed will recombine before being collected, and the current will be correspondingly less (segment *oa* of Fig. 4-20). Higher stresses do not increase the current if all the ions formed are collected. A very small current, on the order of 10^{-21} A/cm² of air, is attributable to cosmic rays and residual natural radioactivity.

Electrons (beta rays) produce much more ionization per path length than gamma rays, because they are slowed down by collisions and lose their energy more quickly. Correspondingly, the slower alpha particles (positive helium nuclei) produce a very dense ionization in air over a short range. For example, a 3-million-eV (MeV) alpha particle has a range in air of 1.7 cm and creates a total of 6.8×10^5 ion pairs. A beta particle (an electron) of the same energy creates only 40 ion pairs per centimeter and has a range of 13 m in air.

It should be noted that ionizing radiation of significant levels has only a small effect on gas dielectric strength. For example, the ionization current produced by a corona discharge from a needle point is typically much higher than that produced by a radiation flux of significant level, 10^{11} gamma photons per square centimeter.

At temperatures increasing above 600°C, it has been shown that thermionic electron emissions from negative conductor surfaces produce significant currents compared with levels typical of electrical insulation.

Since the rate of production of ions by the various sources mentioned above is limited, the current in the gas does not follow Ohm's law, unless the rate of collection of the ions at the electrodes is small compared with the rate of production of these ions, as in the initial part of segment *oa* in Fig. 4-20.

Dielectric Breakdown

Uniform Fields. The dielectric breakdown of gases is a result of an exponential multiplication of free electrons induced by the field. It is generally assumed that the initiation of breakdown

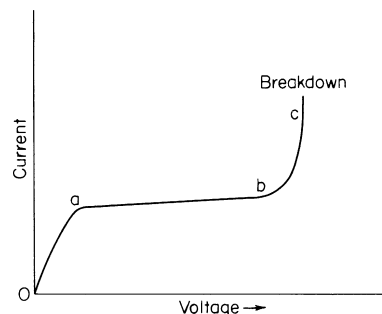


FIGURE 4-20 Current-voltage behavior of a lightly ionized gas.

TABLE 4-8 Relative Dielectric Strengths of Gases
(0.1-in gap)

Air	0.95	CF ₄	1.1
N ₂	1.0	C ₂ F ₆	1.9
CO ₂	0.90	C ₃ F ₈	2.3
H ₂	0.57	C ₄ F ₈ cyclic	2.8
A	0.28	CF ₃ Cl ₂	2.4
Ne	0.13	C ₂ F ₅ Cl	2.6
He	0.14	C ₂ F ₄ Cl ₂	3.3
SF ₆	2.3–2.5		

requires only one electron. However, if only a few electrons are present prior to breakdown, it is not easily possible to measure the trend of current shown in Fig. 4-20. If the breakdown is completed between metal electrodes, the spark develops extremely rapidly into an arc, involving copious emission of electrons from the cathode metal and, if the necessary current flow is permitted, vaporization of metal from the electrodes. Table 4-8 gives the dielectric strength of typical gases.

In uniform electric fields, breakdown occurs at a critical voltage which is a function of the product of the pressure p and spacing d (Paschen's law).

It would be more accurate to consider the gas density-spacing product, since the dielectric strength varies with the temperature only as the latter affects the gas density. It will be noted that the electric field at breakdown decreases as the spacing increases. This is typical of all gases and is due to the fact that a minimum amount of multiplication of electrons must occur before breakdown occurs. A single electron accelerated by the field creates an avalanche which grows exponentially as $e^{\alpha x}$, where x is the distance and α is the Townsend ionization coefficient (electrons formed by collision per centimeter), which increases rapidly with electric field. At small spacings, α and the field must be higher for sufficient multiplication. In divergent electric fields or large spacings, it has been found that when the integral $\int \alpha_E dx$ increases to about 18.4 (10^8 electrons), sufficient space charge develops to produce a streamer type of breakdown. It seems to be apparent that the final step in gas breakdown before arc development is the development of a branched filamentary streamer which proceeds more easily from the positive electrode toward the negative electrode.

Relative Dielectric Strengths of Gases. The relative dielectric strength, with few exceptions, tends upward with increasing molecular weight. There are a number of factors other than molecular or atomic size which influence the retarding effect on electrons. These include ability to absorb electron energy on collision and trap electrons to form negative ions. The noble atomic gases (helium, argon, neon, etc.) are poorest in these respects and have the lowest dielectric strengths. Table 4-8 gives the relative dielectric strengths of a variety of gases at 1 atm pressure at a $p \cdot d$ value of 1 atm $\times$ 0.25 cm. The relative strengths vary with the $p \cdot d$ value, as well as gap geometry, and particularly in divergent fields where corona begins before breakdown. It is best to consult specific references with regard to divergent field breakdown values.

Corona and Breakdown in Nonuniform Fields between Conductors. In nonuniform fields, when the ratio of spacing to conductor radius of curvature is about 3 or less, breakdown occurs without prior corona. The breakdown voltage is controlled by the integral of the Townsend ionization coefficient α across the gap. At larger ratios of spacing to radius of curvature, corona discharge occurs at voltage levels below complete gap breakdown.

Corona in air at atmospheric pressure occurs before breakdown when the ratio of outer to inner radius of coaxial electrodes exceeds 2.72 or where the ratio of gap to sphere radius between spheres exceeds 2.04. These discharges project some distance from the small-radii conductor but do not continue out into the weaker electric field region until a higher voltage level is reached.

Such partial breakdowns are often characterized by rapid pulses of current and radio noise. With some conductors at intermediate voltages between onset and complete breakdown, they blend into a pulseless glow discharge around the conductor. When corona occurs before breakdown, it creates an

ion space charge around the conductor, which modifies the electric field, reducing the stress at sharp conductor points in the intermediate voltage range. At higher voltages, streamers break out of the space-charge region and cross the gap.

The surface voltage stress at which corona begins increases above that for uniform field breakdown stress, since the field to initiate breakdown must extend over a finite distance. An empirical relation developed by Peek is useful for expressing the maximum surface stress for corona onset in air for several geometries of radius r cm:

$$\text{For concentric cylinders: } E = 31\delta \left(1 + \frac{0.308}{\sqrt{\delta r}} \right) \quad \text{kV/cm} \quad (4-74)$$

$$\text{For parallel wires: } E = 29.8\delta \left(1 + \frac{0.301}{\sqrt{\delta r}} \right) \quad \text{kV/cm} \quad (4-75)$$

$$\text{For spheres: } E = 27.2\delta \left(1 + \frac{0.54}{\sqrt{\delta r}} \right) \quad \text{kV/cm} \quad (4-76)$$

where δ is the density of air relative to that at 25°C and 1 atm pressure.

Corona Discharges on Insulator Surfaces. It has been shown by a number of investigators that the discharge-threshold voltage stress on or between insulator surfaces is the same as between metal electrodes. Thus, the threshold voltage for such discharges can be calculated from the series dielectric-capacitance relation for internal gaps of simple shapes, such as plane and coaxial gaps, insulated conductor surfaces, and hollow spherical cavities.

The corona-initiating voltage at a conductor edge on a solid barrier depends on the electric stress concentration and generally on the ratio of the barrier thickness to its dielectric constant, except with low surface resistance. Any absorbed water or conducting film raises the corona threshold voltage by reducing stress concentration at the conductor edge on the surface.

It is sometimes possible to overvolt such gaps considerably prior to the first discharge, and the offset voltage may be below the proper voltage due to surface-charge concentration. With ac voltages, pulse discharges occur regularly back and forth each half cycle, but with dc voltage, the first discharge deposits a surface charge on the insulator surface which must leak away before another discharge can occur. Thus, corona on or between insulator surfaces is very intermittent with steady dc voltages, but discharges occur when the voltage is raised or lowered.

Flashover on Solid Surfaces in Gases. As has been mentioned in the previous section on partial discharges, the breakdown in gases is influenced by the presence of solid insulation between conductors. This insulation increases the electric stress in the gas. A particular case of this is the complete breakdown between conductors across or around solid insulator surfaces. This can occur when the conductors are on the same side of the insulation or on opposite sides. A significant reduction in flashover voltage can occur whenever a significant part of the electric field passes through the insulation. The reduction is influenced by the percentage of electric flux which passes through the solid insulation and the dielectric constant of the insulation.

4.3.3 Insulating Oils and Liquids

General Considerations. Typical insulating liquids are natural or synthetic organic compounds and frequently consist of mixtures of essentially isomeric compounds with some range of molecular weight. The mixture of very similar but not exactly the same molecules, with a range of molecular size and with chain and branched hydrocarbons, prevents crystallization and results in a low freezing point, together with a relatively high boiling point. Typical insulating liquids have permittivities (dielectric constants) of 2 to 7 and a wide range of conductivities depending on their purity. The dc conductivity in these liquids is usually due to dissolved impurities, which are ionized by dissociation. Higher ionized impurity and conductivity levels occur in liquids having higher permittivities and lower viscosities.

The function of insulating liquids is to provide electrical insulation and heat transfer. As insulation, the liquid is used to displace air in the system and provide a medium of high electric strength to fill pores, cracks, and gaps in insulation systems. It is usually necessary to fill and impregnate systems with liquid under vacuum so that all air bubbles are eliminated. If air is completely displaced in all high-electric-field regions, the corona threshold voltage and breakdown voltage for the system are greatly increased. The viscosity selected for a liquid insulation is often a compromise to provide the best balance between electrical insulation and heat transfer and other limitations such as flammability, solidification at low temperatures, and pressure development at high temperatures in sealed systems.

The most commonly used insulating liquids are natural hydrocarbon mineral oils refined to give low conductivity and selected viscosity and vapor-pressure levels for transformer, circuit-breaker, and cable applications. A number of synthetic fluids are also used for particular applications where the higher cost above that of mineral oil is warranted by the requirements of the application or by the improved performance in relation to the apparatus design.

Mineral Insulating Oils. Mineral insulating oils are hydrocarbons (compounds of hydrogen and carbon) refined from crude petroleum deposits from the ground. They consist partly of aliphatic compounds with the general formula C_nH_{2n+2} and C_nH_{2n} , comprising a mixture of straight- and branched-chain and cyclic or partially cyclic compounds. Many oils also contain a sizable fraction of aromatic compounds related to benzene, naphthalene, and derivatives of these with aliphatic side chains. The ratio of aromatic to aliphatic components depends on the source of the oil and its refining treatment. The percentage of aromatics is of importance to the gas-absorption or evaluation characteristics under electrical discharges and to the oxidation characteristics.

The important physical properties of a mineral oil (as for other insulating liquids as well) are listed in Table 4-9 for three types of mineral oils. In addition to these properties, mineral oils which are exposed to air in their application have distinctive oxidation characteristics which vary with type of oil and additives and associated materials.

Many manufacturers now approve the use of any of several brands of mineral insulating oil in their apparatus provided that they meet their specifications which are similar to ASTM D1040, (values from which are tabulated in Table 4-9). Low values of dielectric strength may indicate water or dirt contamination. A high neutralization number will indicate acidity, developed very possibly from oxidation, particularly if the oil has used been already. Presence of sulfur is likely to lead to corrosion of metals in the oil.

The solubility of gases and water in mineral oil is of importance in regard to its function in apparatus. Solubility is proportional to the partial pressure of the gas above the oil

$$S = S_0(p/p_0) \quad (4-77)$$

TABLE 4-9 Characteristic Properties of Insulating Liquids

Type of liquid	Mineral oil		
	Transformer	Cable and capacitor	Solid cable
Specific gravity	0.88	0.885	0.93
Viscosity, Saybolt sec at 37.8°C	57–59	0.100	100
Flash point, °C	135	165	235
Fire point, °C	148	185	280
Pour point, °C	–45	–45	–5
Specific heat	0.425	0.412	
Coefficient of expansion	0.00070		0.00075
Thermal conductivity, cal/(cm) (s) (°C)	0.39		
Dielectric strength,* kV~	30		
Permittivity at 25°C	2.2		
Resistivity, $\Omega \cdot \text{cm} \times 10^{12}$	1–10	50–100	1–10

*ASTM D877.

where S is the amount dissolved at pressure p if the solubility is expressed as the amount S_0 dissolved at pressure p_0 .

The solubility is frequently expressed in volume percent of the oil. Values for solubility of some common gases in transformer oil at atmospheric pressure (760 torr) and 25°C are air 10.8%, nitrogen 9.0%, oxygen 14.5%, carbon dioxide 99.0%, hydrogen 7%, and methane 30% by volume. The solubilities of all the gases, except CO_2 , increase slightly with increasing temperature. Water is dissolved in new transformer oil to the extent of about 60 to 80 ppm at 100% relative humidity and 25°C. The amount dissolved is proportional to the relative humidity. Solubility of water increases with oxidation of the oil and the addition of polar impurities, with which the water becomes associated. Larger quantities of water can be suspended in the oil as fine droplets.

Dielectric Properties of Mineral Oils. The permittivity of mineral insulating oils is low, since they are essentially nonpolar, containing only a few molecules with electric dipole moments. Some oils possess a minor fraction of polar constituents, which have not been identified. These contribute a dipolar character to the dielectric properties at low temperature and/or high frequency. A typical permittivity for American transformer oil at 60 Hz is 2.19 at 25°C, declining almost linearly to 2.11 at 100°C. At low temperatures and high frequencies, values of permittivity as high as 2.85 have been noted in oils with a relatively high level of polar constituents.

The dc conductivity levels of mineral oils range from about $10^{-15} \Omega^{-1} \cdot \text{cm}^{-1}$ for pure new oils up to $10^{-12} \Omega^{-1} \cdot \text{cm}^{-1}$ for contaminated used oils. This conductivity is due to dissociated impurity ions or ions developed by oil oxidation. It increases approximately exponentially with temperature about 1 decade in 80°C.

Alternating-current dissipation-factor values are nearly proportional to the dc conductivity $10^{-13} \Omega^{-1}$, corresponding to a $\tan \delta$ of 0.008. If no electrode polarization or interfacial polarization effects at solid barrier surface are present, the dc conductivity σ should be related to the ac conductivity ($\tan \delta$) by $\sigma = \frac{5}{9} \epsilon' f \tan \delta \times 10^{-12}$ where ϵ' is the dielectric permittivity (Table 4-7) and f is the frequency.

Corona or partial breakdown can occur in mineral oil, as with any liquid or gas, when the electric stress is locally very high and complete breakdown is limited by a solid barrier or large oil gap (as with a needle point in a large gap). Such discharges produce hydrogen and methane gas, and sometimes carbon with larger discharges. Dissolved air is also sometimes released by the discharge. If the gas bubbles formed are not ejected away from the high field, they will reduce the subsequent discharge threshold voltage to as much as 80%. The resistance of insulating oils to partial discharges is measured by two ASTM gassing tests: D2298 (Merrill test) and D2300 (modified Pirelli test). These tests measure the amount of decomposition gas evolved under specified conditions of exposure to partial discharges. A minimum amount of gas is, of course, preferred, particularly in applications for cables or capacitors. In fact, conventional mineral oils are inadequate in this respect for application in modern 60-Hz power capacitor designs.

Deterioration of Oil. Deterioration of oil in apparatus partially open or “breathing” is subject to air oxidation. This leads to acidity and sludge. There is no correlation between the amount of acid and the likelihood of sludging or the amount of sludge. Sludge clogs the ducts, reduces the heat transfer, and accelerates the rate of deterioration. ASTM tests for oxidation of oils are D1904, D1934, D1313, and D1314. Copper and lead and certain other metals accelerate the oxidation of mineral oils. Oils are considerably more stable in nitrogen atmospheres.

Inhibitors are now commonly added both to new and to used oils to delay the oxidation. Diteritary butyl paracresol (DBPC) is the inhibitor most commonly used at present.

Servicing, Filtering, and Treating. Oil in service is usually maintained by testing for acidity, dielectric strength, inhibitor content, interfacial tension, neutralization number, peroxide number, pour point, power factor, refractive index and specific optical dispersion, resistivity, saponification, sludge, corrosive sulfur, viscosity, and water content, as outlined in ASTM D117. These properties indicate various types of contamination or deterioration which might affect the operation of the insulating oil.

Depending on the voltage rating of the apparatus, the oil is maintained above 16 to 22 kV (ASTM test D877). The usual contaminants are water, sludge, acids, and in circuit-breaker oils, carbon. The centrifuge is best suited for removing large quantities of water, heavier solid particles, etc. The blotter filter press is used for the removal of minute quantities of water, fine carbon, etc. In another method, after removing the larger particles, the oil is heated and sprayed into a vacuum chamber, where the water and volatile acids are removed. Sludge and very fine solids are then taken out by a blotter filter press. All units are assembled together so that the process is completed in a single pass. Some work has been done in reclaiming oil by treating it to reduce acidity. One process is similar to the later stages in refining. Another treatment uses activated alumina, Fuller's earth, or silica gel. The IEEE Guide for Maintenance of Insulating Oil is published as *IEEE Standards Publ. 64*.

It has been found that analysis of the dissolved gas in oil or above the oil in oil-insulated transformers and cables is a good diagnostic tool to detect electrical faults, particularly, or deterioration, generally. For example, continuing or intermittent partial discharges produce hydrogen and low-molecular-weight hydrocarbons such as methane, ethane, and ethylene which accumulate in the oil and can be measured accurately to assess the magnitude of the fault. Higher-current arc faults produce acetylene in addition to H_2 and other low-molecular-weight hydrocarbons. Thermal deterioration of cellulosic or paper insulation is indicated by elevated concentrations of CO and CO_2 in the oil.

Synthetic Liquid Insulation. Synthetic chlorinated diphenyl and chlorinated benzene liquids (askarels) have been used widely from the mid-1930s up to the mid-1970s and are still in service in many power capacitors and transformers, where they were adopted for their nonflammability as well as good electrical characteristics. Since the mid-1970s, their use has been banned in most countries due to their alleged toxicity and resistance to biodegradation in the environment. Now, when apparatus containing these fluids, which are commonly referred to as *PCBs*, are taken out of service, environmental regulations in the United States require that the fluid not be released into the environment. Waste fluid should be incinerated at high temperature with HCl reactive absorbent scrubbers in the stack, since this acid gas is a product of the combustion.

New synthetic fluids have been developed and are now widely applied in power capacitors where the electrical stresses are very high. These fluids include aromatic (containing benzene rings) hydrocarbons, some of which have excellent resistance to partial discharges. They are not fire-resistant, however.

Very high boiling, low-vapor-pressure, high-flash-point ($>300^\circ\text{C}$) hydrocarbon oils are being tried for power transformers with some fire resistance. Methods for assessing the risk of fire with such liquids, as well as with silicones, are still being debated.

Perchloroethylene (tetrachloroethylene), a nonpolar liquid, is now in use in sealed medium-power transformers, where nonflammability is required. With a boiling point at atmospheric pressure of 121°C , this fluid is completely nonflammable. It is also widely used in dry cleaning. Other important classes of synthetic insulating fluids are discussed in the following sections.

Fluorocarbon Liquids. A number of nonpolar nonflammable perfluorinated aliphatic compounds, in which the hydrogen has been completely replaced by fluorine, are available with different ranges of viscosity and boiling point from below room temperature to more than 200°C . These compounds have low permittivities (near 2.0) and very low conductivity. They are inert chemically and have low solubilities for most other materials. The chemical formula for these compounds is one of the following: C_nF_{2n} , C_nF_{2n+2} , or $C_nF_{2n}O$. The presence of the oxygen in the latter formula does not seem to reduce the stability. These compounds have been used for filling electronic apparatus and large transformers to give high heat-transfer rates together with high dielectric strength. The vapors of these liquids also have high dielectric strengths.

Silicone Fluids. These fluids, chemically formed from Si—O chains with organic (usually methyl) side groups, have a high thermal stability, low temperature coefficient of viscosity, low dielectric losses, and high dielectric strength. They can be obtained with various levels of viscosity and correlated vapor pressures. Rated service temperatures extend from -65 to 200°C , some having short-time capability up to 300°C . Their permittivity is about 2.6 to 2.7, declining with increasing temperature. These fluids have a tendency to form heavier carbon tracks than other

insulating liquids when breakdown occurs. They cannot be considered fireproof but will reduce the risk of fire due to their low vapor pressure.

Ester Fluids. There are a few applications, mostly for capacitors, where organic ester compounds are used. These liquids have a somewhat higher permittivity, in the range of about 4 to 7, depending on the ratio of ester groups to hydrocarbon chain lengths. Their conductivities are generally somewhat higher than those of the other insulating liquids discussed here. The compounds are easily subject to hydrolysis with water to form acids and alcohols and should be kept dry, particularly if the temperature is raised. Their thermal stability is poor. Specifically, dibutyl sebacate has been used in high-frequency capacitors and castor oil in energy-storage capacitors.

4.3.4 Insulated Conductors

Insulated conductors vary from those carrying only a few volts to those carrying thousands of volts. They range from low-voltage bell wire with conductor gage of 22 to 24 to power cables with conductors of 2000 kcmil or 1013 mm² in cross-sectional area. The conductors can be round, rectangular, braided, or stranded. They can be of aluminum or copper. The insulation can be thin as in magnet wire or thick as in underground or marine cables. The insulation system can vary with functional application. It can be extruded or taped. It can be thermoplastic or thermoset. It can be a polymer in combination with cotton or glass cloth. There can be several different layers with different functional roles. Some of the applications for insulated conductors are communications, control, bell, building, hookup, fixture, appliance, and motor lead. The insulation technology for magnet wire and for power cables has been studied extensively because of the severe stresses seen by these insulation systems.

Flexible Cords. Flexible cords and cables cover appliance and lamp cords, extension cords for home or industrial use, elevator traveling cables, decorative-lighting wires and cords, mobile home wiring, and wiring for appliances that get hot (e.g., hot plates, irons, cooking appliances). The requirements for these cables vary a great deal with application. They must be engineered to be water-resistant, impact-resistant, temperature-tolerant, flex-tolerant, linearly strong, and flame-resistant and have good electrical insulation characteristics.

Magnet Wire Insulation. The term *magnet wire* includes an extremely broad range of sizes of both round and rectangular conductors used in electrical apparatus. Common round-wire sizes for copper are AWG No. 42 (0.0025 in) to AWG No. 8 (0.1285 in). A significant volume of aluminum magnet wire is produced in the size range of AWG No. 4 to AWG No. 26. Ultrafine sizes of round wire, used in very small devices, range as low as AWG No. 60 for copper and AWG No. 52 for aluminum.

Approximately 20 different “enamels” are used commercially at present in insulating magnet wire. Magnet wire insulations are high in electrical, physical, and thermal performance and best in space factor. The most widely used polymers for film-insulated magnet wire are based on polyvinyl acetals, polyesters, polyamideimides, polyimides, polyamides, and polyurethanes. Many magnet wire constructions use different layers of these polymer types to achieve the best combination of properties. The most commonly used magnet wire is NEMA MW-35C, Class 200, which is constructed with a polyester basecoat and a polyamideimide topcoat. Polyurethanes are employed where ease of solderability without solvent or mechanical stripping is required. The thermal class of polyurethane insulations has been increased up to Class 155 and even Class 180. Magnet wire products also are produced with fabric layers (fiberglass or Dacron-fiberglass) served over bare or conventional film-insulated magnet wire. Self-bonding magnet wire is produced with a thermoplastic cement as the outer layer, which can be heat-activated to bond the wires together.

Power Cables. Insulated power cables are used extensively in underground residential distribution. There has been extensive replacement of PILC, or paper in lead cable, with extruded polymer-insulated cables. Although PILC is still dominant for underground transmission cables, extruded polymeric cables are also beginning to be used for these high-voltage applications. Typical cable sizes with the cross section of the conductor are shown in the Table 4-10.

TABLE 4-10 Typical Cable Sizes

Cable size	Conductor cross section, mm ²
AWG 2	33.6
AWG 1	42.4
AWG 1/0	53.5
AWG 2/0	67.4
AWG 3/0	85.0
AWG 4/0	107.2
500 kcmil	253.5
750 kcmil	379.5
1000 kcmil	507.0
2000 kcmil	1013.0

Typically, a cable rated at 15 kV will have insulation of wall thickness 175 mil (4.45 mm); one rated at 35 kV will have a wall thickness of 345 mil (8.76 mm); one rated at 69 kV will have insulation thickness of 650 mil (16.5 mm); and a 138-kV cable will have insulation of wall thickness 850 mil (21.6 mm). A cable construction includes the conductor shield, insulation, and insulation shield. In addition, most cables these days have a jacket to diminish moisture penetration into the insulation.

The conductor shield is a semiconductive material applied to the conductor to smooth out the stress. Since the conductors, especially the stranded conductors, have “bumps” that can enhance the field, the role of the semiconductor is to present an even voltage stress to the insulation. The insulation shield fulfills a similar role on the outer surface of the insulation. Grit, or especially metal particles, can be sites where breakdown begins. A clean interface and a semiconductive material prevent such sites from forming. The formulation of the conductor shield and the insulation shield is different. The formulation also depends on the insulating material used. A number of different materials have been used as the matrix material for semiconductive shields. These include low-density polyethylene (LDPE), ethylene–ethyl acrylate (EEA), ethylene–vinyl acetate (EVA), ethylene–propylene rubber (EPR), ethylene–propylene diene monomer (EPDM), butyl rubber, and various proprietary formulations. These materials, in themselves, are not conducting. They are made conducting by loading the polymer with carbon.

There are two insulations in use for power cables. One is cross-linked polyethylene (XLPE) and the other is ethylene–propylene rubber (EPR). These insulating materials will be described in greater detail in the following paragraphs.

Most of the cables being installed in the latter part of the 1990s are jacketed. The jacket provides protection against oil, grease, and chemicals. However, the primary role played by the jacket is to slow down the ingress of moisture, since moisture in the presence of an electric field causes the insulation to degrade by a process called *treeing*. One of the materials used extensively as a jacket material is linear low-density polyethylene (LLDPE). Jackets are approximately 50 mil (1.27 mm) thick. The discussion thus far has not described the chemistry of each of these insulating materials. The terms *thermoset* and *thermoplastic* are used without explanation. Material names such as PE, PTFE, PVC, and silicones are used without characterizing the chemistry or structure.

A *thermoplastic* resin is one with a melting point. With rising temperature, a thermoplastic resin first undergoes a glass-transition temperature (T_g) and then a crystalline melting point (T_m). Below the glass-transition temperature, a polymer is rigid and exhibits properties associated with the crystalline state. Above the glass-transition temperature, the material becomes plastic and viscous, and the material starts to slowly approach the structure of the liquid state. The glass-transition state can be detected by plotting the dielectric constant, refractive index, specific heat, coefficient of expansion, or electrical conductivity as a function of temperature.

There is one characteristic slope below the glass-transition state and another steeper slope above the glass-transition temperature. Approximate values for T_g and T_m for polyethylene are -128 and 115°C , and for polystyrene they are 80 and 240°C . It is difficult to give exact values for a given generic polymer. This is so because the exact value will depend a great deal on the variation in the character of a particular polymer, with all the variations being grouped together and called by a

common name. For example, for polyethylene, the molecular weight (the degree of polymerization) of the resin, the degree of branching, and the size or length of the branches will affect both T_g and T_m . With polyvinyl chloride, the stereoregularity, copolymerization, and plasticization all will affect T_g and T_m .

A *thermoset* resin does not exhibit a visible melting point. An epoxy or a phenolic resin has a three-dimensional network structure. The three-dimensional structure results in a rigid framework that cannot be made fluid without breaking a large number of bonds. The thermoplastic resins, on the other hand, are linear. They might be thought of as strands of spaghetti. The strands can slip by one another and can be fluid. The analogy to a bowl of spaghetti can be used in understanding how a thermoset material can be formed by cross-linking a thermoplastic polymer such as polyethylene. The cross-linking reaction forms bonds between the linear strands of polyethylene to form a three-dimensional structure. To visualize the cross-linking, an analogy that can be used is that of the bowl of spaghetti left in a refrigerator overnight. Once the strands of spaghetti stick together, the mass is no longer fluid. The mass can be taken out of the bowl, and it will retain the shape of the bowl. The only way to fluidize this spaghetti is to break most or all the bonds formed between the individual strands.

Some of the insulation materials used for insulated conductors are polyethylene (PE), ethylene-propylene rubber (EPR), polyvinyl chloride (PVC), fluorinated ethylene propylene (FEP), ethylene chlorotrifluoroethylene, polytetrafluoroethylene (PTFE), butyl rubber, neoprene, nitrile-butadiene rubber (NBR), latex, polyamide, and polyimide.

Polyethylene is made by polymerizing ethylene, a gas with a boiling point of -104°C . A reaction carried out at high temperature (up to 250°C) and high pressure (between 1000 and 3000 atm) produces low-density polyethylene. The reason for the low density is that the short and long branches on the long chains prevent the chains from packing efficiently into a crystalline mass. The use of Ziegler-Natta catalysts results in high-density polyethylene. The use of the catalyst results in less branching and thereby a polymer that can pack more efficiently into crystalline domains. Recently, shape-selective catalysts have become available that produce polyethylene polymers that can be made with designer properties. Even though polyethylene consists of chains of carbons, the properties can vary depending on molecular weight and molecular shape. Polyethylene sold for insulating purposes has only small amounts of additives. There is always some antioxidant. For cross-linked polyethylene, the residues of the cross-linking agent are present. Additives to inhibit treeing are added.

Ethylene-propylene rubber is a copolymer made from ethylene and propylene. The physical properties of the neat polymer are such that it is not useful unless compounded. The finished compounded product has as much as 40 to 50% filler content. Fillers consist of clays, calcium carbonate, barium sulfate, or various types of silica. In addition to the filler, EPR is compounded with plasticizer, antioxidants, flame retardants, process aids, ion scavengers, coupling agents, a curing coagent, and a curative.

Polyvinyl chloride is a polymer made from vinyl chloride, a gas boiling at -14°C . It is partially syndiotactic; that is, the stereochemistry of the carbons on which the chlorines are attached is more or less alternating. By being only partially syndiotactic, the crystallinity is low. However, the polymer is still fairly rigid, and for use where flexibility is desired, the polymer must be plasticized.

Dibutylphthalate is often used as a plasticizer. In addition to plasticizers, PVC contains heat and light stabilizers. Oxides, hydroxides, or fatty acid salts of lead, barium, tin, or cadmium are typical stabilizers.

Polytetrafluoroethylene (or Teflon) is a polymer made from tetrafluoroethylene, a nontoxic gas boiling at -76°C . It is a linear polymer consisting of chains made of CF_2 units. Its crystallinity is quite high, and its crystalline melting point is 327°C . It is resistant to almost all reagents, even up to the boiling point of the reagent. It is attacked only by molten alkali metals or the alkali metal dissolved in liquid ammonia. Polytetrafluoroethylene exhibits excellent electrical properties. It has a low dielectric constant and a low loss factor. These electrical properties do not change even when the polymer is kept at 250°C for long periods of time.

Fluorinated ethylene propylene is a copolymer made from tetrafluoroethylene and hexafluoropropylene. It compares in toughness, chemical inertness, and heat stability to polytetrafluoroethylene (PTFE).

Polychlorotrifluoroethylene has performance properties that are surpassed only by PTFE and FEP. The crystalline melting point is 218°C, as compared with 327°C for PTFE. It retains useful properties to 150°C, as opposed to 250°C for PTFE. The advantage for polychlorotrifluoroethylene is that its melt viscosity is so low enough that molding and extrusion become more feasible than for PTFE and FEP.

Polyamides or Nylons are long-chain linear polymers made by molecules linked by amide linkages. Nylon 66 is made from hexamethylene diamine and adipic acid. Nylon 66 exhibits high strength, elasticity, toughness, and abrasion resistance. Nylon 6 is made from caprolactam, a cyclic amide. To form a polymer, the caprolactam opens and the amine group and carboxylic acid group form intermolecular amide links rather than the intramolecular amide link in the cyclic compound.

Polyimides are polymers connected by imide bonds. An amide is formed when the OH group of a carboxylic acid is replaced by the NH of an amine. An imide is a related structure formed when the noncarbonyl oxygen of an acid anhydride is replaced by a nitrogen of an amine. A polyimide is usually formed from an aromatic diamine and an aromatic dianhydride. The aromatic nature of the polyimide imparts thermal stability.

Rubbers used for electrical insulation can be either natural rubber or one of the synthetic rubbers. Natural rubber is obtained from the latex of different plants. The primary commercial source is the tree *Hevea brasiliensis*. Natural rubber is an isoprenoid compound wherein the isoprene (2-methyl-1,3-butadiene) is the unit of a high-molecular-weight polymer with a degree of polymerization of around 5000. Rubber without processing is too gummy to be of practical use. It is vulcanized (cross-linked) by reaction with sulfur. Natural rubber is flexible and elastic and exhibits good electrical characteristics.

Butyl rubbers are synthetic rubbers made by copolymerizing isobutylene (2-methyl-1-propene) with a small amount of isoprene. The purpose of isoprene is to introduce a double bond into the polymer chain so that it can be cross-linked. Butyl rubbers are mostly amorphous, with crystallization taking place on stretching. They are characterized by showing a low permeability to gases, thus making them the material of choice for inner tubes of automobile tires. They are reasonably resistant to oxidative aging. Butyl rubbers have good electrical properties.

Polychloroprene or *neoprene* is a generic term for polymers or copolymers of chloroprene (2-chloro-1,3-butadiene). Neoprene is an excellent rubber with good oil resistance. It has resistance to oxidative degradation, and is stable at high temperatures. Its properties are such that it would make excellent automobile tires, but the cost of the polymer makes it noncompetitive for this market. Its desirable properties are exploited for wire and cable insulations.

Nitrile rubbers are polymers of butadiene and acrylonitrile. Nitrile rubbers are used where oil resistance is needed. The degree of oil resistance varies with acrylonitrile content of the copolymer. With 18% acrylonitrile content, the oil resistance is only fair. With 40% acrylonitrile content, the oil resistance is excellent. The oil resistance is characterized by retention of low swelling, good tensile strength, and good abrasion resistance after being immersed in gasoline or oil. Nitrile rubbers can be used in contact with water or antifreeze. For use in wire insulation where oil resistance is needed, nitrile rubber is slightly better than neoprene.

4.3.5 Thermal Conductivity of Electrical Insulating Materials

One of the general characteristics of electrical insulating materials is that they are also good thermal insulating materials. This is true, in varying degrees, for the entire spectrum of insulating materials, including air, fluids, plastics, glasses, and ceramics. While the thermal insulating properties of electrical insulating materials are not especially important for electrical and electronic designs which are not heat sensitive, modern designs are increasingly heat sensitive. This is often because higher power levels are being dissipated from smaller part volumes, thus tending to raise the temperature of critical elements of the product design. This results in several adverse effects, including degradation of electrical performance and degradation of many insulating materials, especially insulating papers and plastics. The net result is reduced life and/or reduced reliability of the electrical or electronic part. To maximize life and reliability, much effort has been devoted to data and guidelines for gaining the highest possible thermal conductivity, consistent with optimization of product design limitations such

as fabrication, cost, and environmental stresses. This section will present data and guidelines which will be useful to electrical and electronic designers in selection of electrical insulating materials for best meeting thermal design requirements. Also, methods of determining thermal conductivity K will be described.

Basic Thermal-Conductivity Data. The thermal-conductivity values for a range of materials commonly used in electrical design are shown in Table 4-11. These data show the ranking of the range of materials, both conductors and insulating materials, from high to low. The magnitude of the differences in conductor and plastic thermal-conductivity values can be seen. Note that one ceramic, 95% beryllia, has a higher thermal-conductivity value than some metals—thus making beryllia highly considered for high-heat-dissipating designs which allow its use. Thermal conductivity is variously reported in many different units, and convenient conversions are shown in Table 4-12.

Values of thermal conductivity do not change drastically up to 100°C or higher, and hence only a single value is usually given for plastics. For higher-temperature applications, such as with ceramics, the temperature effect should be considered. In addition to bulk insulating materials, insulating coatings are frequently used.

TABLE 4-11 Thermal Conductivity of Materials Commonly Used for Electrical Design

Material	Thermal conductivity	
	W/(in)(°C)	Btu/(h)(ft)(°F)
Silver	10.6	241
Copper	9.6	220
Eutectic bond	7.50	171.23
Gold	7.5	171
Aluminum	5.5	125
Beryllia 95%	3.9	90.0
Molybdenum	3.7	84
Cadmium	2.3	53
Nickel	2.29	52.02
Silicon	2.13	48.55
Palladium	1.79	40.46
Platinum	1.75	39.88
Chromium	1.75	39.88
Tin	1.63	36.99
Steel	1.22	27.85
Solder (60–40)	0.91	20.78
Lead	0.83	18.9
Alumina 95%	0.66	15.0
Kovar	0.49	11.1
Epoxy resin, BeO-filled	0.088	2.00
Silicone RTV, BeO-filled	0.066	1.5
Quartz	0.05	1.41
Silicon dioxide	0.035	0.799
Borosilicate glass	0.026	0.59
Glass frit	0.024	0.569
Conductive epoxy	0.020	0.457
Sylgard resin	0.009	0.21
Epoxy glass laminate	0.007	0.17
Doryl cement	0.007	0.17
Epoxy resin, unfilled	0.004	0.10
Silicone RTV, BeO-filled	0.004	0.10
Air		0.016

TABLE 4-12 Thermal-Conductivity Conversion Factors

From	To			
	$\frac{(\text{cal})(\text{cm})}{(\text{s})(\text{cm}^2)(^\circ\text{C})}$	$\frac{(\text{W})(\text{cm})}{(\text{cm}^2)(^\circ\text{C})}$	$\frac{(\text{W})(\text{in})}{(\text{in}^2)(^\circ\text{C})}$	$\frac{(\text{Btu})(\text{ft})}{(\text{h})(\text{ft}^2)(^\circ\text{F})}$
$\frac{(\text{cal})(\text{cm})}{(\text{s})(\text{cm}^2)(^\circ\text{C})}$	1	4.18	10.62	241.9
$\frac{(\text{W})(\text{cm})}{(\text{cm}^2)(^\circ\text{C})}$	2.39×10^{-1}	1	2.54	57.8
$\frac{(\text{W})(\text{in})}{(\text{in}^2)(^\circ\text{C})}$	9.43×10^{-2}	3.93×10^{-1}	1	22.83
$\frac{(\text{Btu})(\text{ft})}{(\text{h})(\text{ft}^2)(^\circ\text{F})}$	4.13×10^{-3}	1.73×10^{-2}	4.38×10^{-2}	1

Thermal-Conductivity Measurements. The recognized primary technique for measuring thermal conductivity of insulating materials is the guarded-hot-plate method (ASTM C177). A schematic of the apparatus is shown in Fig. 4-21. The purpose of the guard heater is to prevent heat flow in all but the axial (up and down in the schematic) direction by establishing isothermal surfaces on the specimen's hot side. With this condition established and by measuring the temperature difference across the sample, the electrical power to the main heater area and the sample thickness, the K factor, can be calculated as

$$K = \frac{QX}{2A \Delta T} \quad (4-78)$$

Instruments are available for this test which use automatic means to control the guard temperature and record the sample ΔT . Unfortunately this test is fairly expensive.

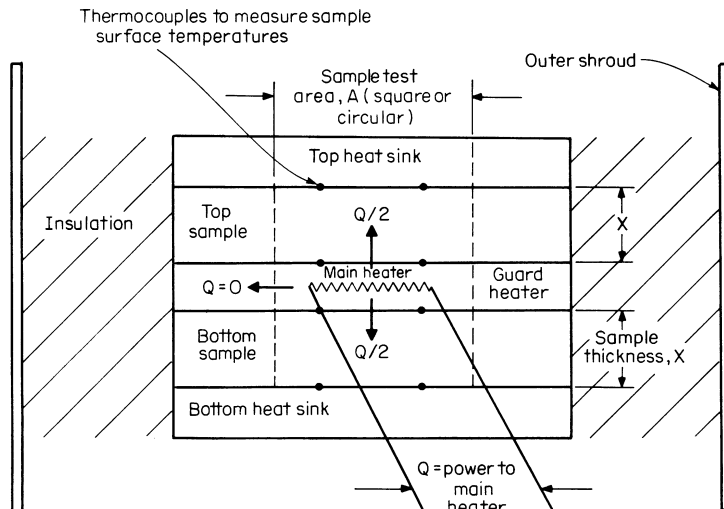


FIGURE 4-21 Schematic assembly of guarded hot plate.

Another technique uses a heat-flow sensor, which is a calibrated thermopile, in series with the heater, specimen, and cold sink. This method avoids the guard heater and requires only one specimen. This secondary technique is described in ASTM C518.

4.4 STRUCTURAL MATERIALS

4.4.1 Definitions of Properties

Stress. *Stress* is the intensity at a point in a body of the internal forces or components of force that act on a given plane through the point. Stress is expressed in force per unit of area (pounds per square inch, kilograms per square millimeter, etc.). There are three kinds of stress: tensile, compressive, and shearing. *Flexure* involves a combination of tensile and compressive stress. *Torsion* involves shearing stress. It is customary to compute stress on the basis of the original dimensions of the cross section of the body, though “true stress” in tension or compression is sometimes calculated from the area of the time a given stress exists rather than from the original area.

Strain. *Strain* is a measure of the change, due to a force, in the size or shape of a body referred to its original size or shape. Strain is a nondimensional quantity but is frequently expressed in inches per inch, etc. Under tensile or compressive stress, strain is measured along the dimension under consideration. *Shear strain* is defined as the tangent of the angular change between two lines originally perpendicular to each other.

Stress-Strain Diagram. A *stress-strain diagram* is a diagram plotted with values of stress as ordinates and values of strain as abscissas. Diagrams plotted with values of applied load, moment, or torque as ordinates and with values of deformation, deflection, or angle of twist as abscissas are sometimes referred to as stress-strain diagrams but are more correctly called *load-deformation diagrams*. The stress-strain diagram for some materials is affected by the rate of application of the load, by cycles of previous loading, and again by the time during which the load is held constant at specified values; for precise testing, these conditions should be stated definitely in order that the complete significance of any particular diagram may be clearly understood.

Modulus of Elasticity. The *modulus of elasticity* is the ratio of stress to corresponding strain below the proportional limit. For many materials, the stress-strain diagram is approximately a straight line below a more or less well-defined stress known as the *proportional limit*. Since there are three kinds of stress, there are three moduli of elasticity for a material, that is, the modulus in tension, the modulus in compression, and the modulus in shear. The value in tension is practically the same, for most ductile metals, as the modulus in compression; the modulus in shear is only about 0.36 to 0.42 of the modulus in tension. The modulus is expressed in pounds per square inch (or kilograms per square millimeter) and measures the elastic *stiffness* (the ability to resist elastic deformation under stress) of the material.

Elastic Strength. To the user and the designer of machines or structures, one significant value to be determined is a *limiting stress below which the permanent distortion of the material is so small that the structural damage is negligible and above which it is not negligible*. The amount of plastic distortion which may be regarded as negligible varies widely for different materials and for different structural or machine parts. In connection with this limiting stress for elastic action, a number of technical terms are in use; some of them are

1. **Elastic Limit.** The greatest stress which a material is capable of withstanding without a permanent deformation remaining on release of stress. Determination of the elastic limit involves repeated application and release of a series of increasing loads until a set is observed upon release of load. Since the elastic limit of many materials is fairly close to the proportional limit, the latter is sometimes accepted as equivalent to the elastic limit for certain materials. There is, however, no

fundamental relation between elastic limit and proportional limit. Obviously, the value of the elastic limit determined will be affected by the sensitivity of apparatus used.

2. **Proportional Limit.** The greatest stress which a material is capable of withstanding without a deviation from proportionality of stress to strain. The statement that the stresses are proportional to strains below the proportional limit is known as *Hooke's Law*. The numerical values of the proportional limit are influenced by methods and instruments used in testing and the scales used for plotting diagrams.
3. **Yield Point.** The lowest stress at which marked increase in strain of the material occurs *without increase in load*. If the stress-strain curve shows no abrupt or sudden yielding of this nature, then there is no yield point. Iron and low-carbon steels have yield points, but most metals do not, including iron and low-carbon steels immediately after they have been plastically deformed at ordinary temperatures.
4. **Yield Strength.** The stress at which a material exhibits a specified limiting permanent set. Its determination involves the selection of an amount of permanent set that is considered the maximum amount of plastic yielding which the material can exhibit, in the particular service condition for which the material is intended, without appreciable structural damage. A set of 0.2% has been used for several ductile metals, and values of yield strength for various metals are for 0.2% set unless otherwise stated. On the stress-strain diagram for the material (Fig. 4-22) this arbitrary set is laid off as q along the strain axis, and the line mn drawn parallel to OA , the straight portion of the diagram. Since the stress-strain diagram for release of load is approximately parallel to OA , the intersection r may be regarded as determining the stress at the yield strength. The yield strength is generally used to determine the elastic strength for materials whose stress-strain curve in the region pr is a smooth curve of gradual curvature.

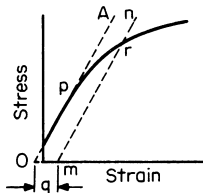


FIGURE 4-22 Yield strength of a material having no well-defined yield point.

Ultimate Strength. *Ultimate strength (tensile strength or compressive strength)* is the maximum stress which a material will sustain when slowly loaded to rupture. Ultimate strength is computed from the maximum load carried during a test and the original cross-sectional area of the specimen. For materials that fail in compression with a shattering fracture, the compressive strength has a definite value, but for materials that do not fracture, the compressive strength is an arbitrary value depending on the degree of distortion which is regarded as indicating complete failure of the material. In tensile tests of many materials, especially those having appreciable ductility, failure does not occur at the stress corresponding to the ultimate strength. For such materials, localized deformation, or necking, occurs and the nominal stress decreases because of the rapidly decreasing cross-sectional area until failure occurs.

Shearing Strength. *Shearing strength* is the maximum shearing stress which a material is capable of developing. The remarks in the preceding paragraph regarding methods of failure are also applicable to failures in shear. Owing to experimental difficulties of obtaining true shearing strength, the values of modulus of rupture in torsion are usually reported as indicative of the shearing strength.

Modulus of Rupture. *Modulus of rupture* in flexure (or torsion) is the term applied to the computed stress, in the extreme fiber of a specimen tested to failure under flexure (or torsion), when computed by the arbitrary application of the formula for stress with disregard of the fact that the stresses exceed the proportional limit. Hence, the modulus of rupture does not give the true stress in the member but is useful only as a basis of comparison of relative strengths of materials.

Ductility. *Ductility* is that property of a material which enables it to acquire large permanent deformation and at the same time develop relatively large stresses (as drawing into a wire). Although ductility is a highly desirable property required by almost all specifications for metals, the quantitative

amount needed for structural applications is not entirely clear but probably does not exceed about 3% elongation after the structure is fabricated. The commonly used measures of ductility are

1. *Elongation* is the ratio of the increase of length of a specimen, after rupture under tensile stress, to the original gage length; it is usually expressed in percent. The percentage of elongation for any given material depends upon the gage length, which should always be specified.
2. *Reduction of area or contraction of area* is the ratio of the difference between the original and the fractured cross section to the original cross-sectional area; it is usually expressed as a percentage.
3. *Bend test* measures the angle through which a given specimen of material can be bent, at a specified temperature, without cracking. In some cases, the maximum angle through which the specimen can be bent around a certain diameter or the number of bendings back and forth through a stated angle are measured. In other cases, the elongation in a given gage length across the crack on the tension side of the bend specimen is measured.

Plasticity. *Plasticity* permits a material to assume permanent deformations under loads without recovery of the strain when the loads are removed. Plasticity permits shaping of metal parts by plastic deformation; plastic materials deform instead of fracturing under load.

Brittleness. *Brittleness* is defined as the ability of a material to fracture under stress with little or no plastic deformation. Brittleness implies a lack of plasticity.

Resilience. *Resilience* is the amount of strain energy (or work) which may be recovered from a stressed body when the loads causing the stresses are removed. Within the elastic limit, the work done in deforming the bar is completely recovered upon removal of the loads; the total amount of work done in stressing a unit volume of the material to the elastic limit is called the *modulus of resilience*.

Toughness. *Toughness* is the ability to withstand large stresses accompanied by large strains before fracture. The toughness is usually measured by the total work done in stressing a unit volume of the material to complete fracture and may be interpreted as the total area under the stress-strain curve. Ductility differs from toughness in that it deals only with the ability of the material to deform, whereas toughness is measured by the energy-absorbing capacity of the material.

Impact Resistance. The ability of a material to resist impact or energy loads without permanent distortion is measured by the modulus of resilience. The ultimate resistance to impact before fracture is measured by the toughness of the material. For members with abrupt changes of section (holes, keyways, fillets, etc.), the resistance to a rapidly applied load depends greatly on the *notch sensitivity* (the resistance to the formation and spread of a crack); above certain critical velocities of loading and below certain critical temperatures, the impact strength is greatly reduced. Relative notch sensitivity under repeated loads is not the same as that in a single-blow notched-bar test. Impact values are influenced by speed of straining, shape and size of specimen, and type of testing machine.

Charpy or *Izod* impact bend tests measure the energy required to fracture small notched specimens (1 cm²) under a single blow. These tests are used as an indication of toughness, a property that is very sensitive to the composition and thermal-mechanical history of the material. Tests should be carried out over a range of temperatures to determine the temperature at which the alloy fails by brittle rather than ductile failure.

Fracture Mechanics. Three primary factors have been identified that control the susceptibility of a structure to brittle failure: material toughness (affected by composition and metallurgical structure as well as temperature, strain rate, and constraints to plastic yielding), flaw size (internal discontinuities such as porosity or small cracks from welding, fatigue, and fabrication), and stress level (applied or residual). Fracture mechanics attempt to interrelate these variables in order to predict the

occurrence of brittle fracture on a quantitative design basis rather than depend on qualitative relationships between experience and results of impact tests such as Izod and Charpy. Fracture mechanics has had excellent success when applied to high-strength materials. The material parameter defined, called the *fracture toughness* K_{IC} , can be measured experimentally and used to specify safe loading conditions in the presence of a given size and geometry of flaw.

Hardness. *Hardness* is the resistance which a material offers to small, localized plastic deformations developed by specific operations such as scratching, abrasion, cutting, or penetration of the surface. Hardness does not imply brittleness, as a hard steel may be tough and ductile. The standard Brinell hardness test is made by pressing a hardened steel ball against a smooth, flat surface under certain standard conditions; the Brinell hardness number is the quotient of the applied load divided by the area of the surface of the impression. A different method of test is employed in the Shore scleroscope, in which a small, pointed hammer is allowed to fall from a definite height onto the material, and the hardness is measured by the height of the rebound, which is automatically indicated on a scale. The Rockwell hardness machine measures the depth of penetration in the metal produced by a definite load on a small indenter of spherical or conical shape. Vickers or Tukon hardness machines measure hardness on a microscopic scale. The dimensions of the impression of a lightly loaded diamond pyramid indenter on a polished surface are related to hardness number.

Fatigue Strength. *Fatigue strength (fatigue limit)* is a limiting stress below which no evidence of failure by progressive fracture can be detected after the completion of a very large number of repetitions of a definite cycle of stress. The fatigue limits usually reported are those for completely reversed cycles of flexural stress in polished specimens. For stress cycles in which an alternating stress is superimposed on a steady stress, the endurance limit (based on the maximum stress in the cycle) is somewhat higher. Most ferrous metals have well-defined limits, whereas the fatigue strength of many nonferrous metals is arbitrarily listed as the maximum stress that is just insufficient to cause fracture after some definite number of cycles of stress, which should always be stated. The fatigue strength of actual members containing notches (holes, fillets, surface scratches, etc.) is greatly reduced and depends entirely on the “stress-raising” effect of these discontinuities and the sensitivity of the material to the localized stresses at the notch.

Composition and Structure. Chemical analysis is employed to determine whether component elements are present within specified amounts and impurity elements are held below specified limits. Mechanical and physical properties, however, depend on the size, shape, composition, and distribution of the crystalline constituents that make up the structure of the alloy. Chemical analysis does not reveal these features of the structure. Metallographic techniques, which involve examination of carefully polished and etched surfaces by optical and electron microscopy or x-ray methods, are required to provide this vital information. Nondestructive testing (NDT) methods are useful in detecting the presence of flaws of various kinds in finished parts and structures. These techniques depend on the interference of the defect with some easily measured physical property, such as x-ray absorption, magnetic susceptibility, propagation of acoustical waves, or electrical conductivity. NDT techniques have particular application where defects are difficult to detect and quite likely to occur (as in welded structures), and where high-integrity performance requires 100% inspection.

Aging. *Aging* is a spontaneous change in properties of a metal with time after a heat-treatment or a cold-working operation. Aging tends to restore the material to an equilibrium condition and to remove the unstable condition induced by the prior operation, and usually results in increased strength of the metal with corresponding loss of ductility. The fundamental action involved is generally one of precipitation of hardening elements from the solid solution, and the process can usually be hastened by slight increase in temperature. This is a very important strengthening mechanism in a variety of ferrous and nonferrous alloys, for example, high-strength aluminum alloys.

Corrosion Resistance. There is no universal method of determining corrosion resistance, because different types of exposures ordinarily produce entirely dissimilar results on the same material. In general, the subject of corrosion is rather complicated; in some cases, corrosive attack appears to be

chiefly chemical in nature, while in others the attack is by electrolysis. Owing to the great diversity of materials exposed to corrosive influences in service and the wide range of service conditions, it is impracticable to formulate any universal measure of corrosion resistance. If the service life is likely to be determined by corrosion resistance, the degree of impairment which marks the end of usefulness ordinarily will be established by considerations of safety and reliability or perhaps of appearance. Corrosion testing is conducted in general by two methods: (1) normal exposure in service with periodic observations of corrosive action as it progresses under such conditions, and (2) some type of artificially accelerated test, which may serve merely to obtain comparative results or, again, may simulate the conditions of service exposure.

Powder Metallurgy. Many alloys and metallic aggregates having unusual and very valuable properties are being produced commercially by mixing metal powders, pressing in dies to desired shapes, and sintering at high temperatures. Parts may be produced to close dimensional tolerance, and the process enables the mixing of dissimilar materials which will not normally alloy or which cannot be cast because of insolubility of the constituents. Wide use of powder metallurgy is made in producing copper-molybdenum alloys for contact electrodes for spot welding, extremely hard cemented tungsten carbide tips for use in metal cutting tools, and copper-base alloys containing either graphite particles or a controlled dispersion of porosity for bearings of the “oilless” or oil-retaining types. Silver-nickel and silver-molybdenum alloys (tungsten or graphite may be added) for contact materials having high conductivity but good resistance to fusing can be produced by the method. Powdered iron is being used to manufacture gears and small complex parts where the savings in weight of metal and machining costs are able to offset the additional cost of metal and processing in the powdered form. Small Alnico magnets of involved shape which are exceedingly difficult to cast or machine can be produced efficiently from metallic powders and require little or no finishing. Solid mixtures of metals and nonmetals, such as asbestos, can be produced to meet special requirements. The size and shape of powder particles, pressing temperature and pressure, sintering temperature and time, all affect the final density, structure, and physical properties.

4.4.2 Structural Iron and Steel

Classification of Ferrous Materials. Iron and steel may be classified on the basis of composition, use, shape, method of manufacture, etc. Some of the more important ferrous alloys are described in the sections below.

Ingot iron is commercially pure iron and contains a maximum of 0.15% total impurities. It is very soft and ductile and can undergo severe cold-forming operations. It has a wide variety of applications based on its formability. Its purity results in good corrosion resistance and electrical properties, and many applications are based on these features. The average tensile properties of Armco ingot iron plates are tensile strength 320 MPa (46,000 lb/in²); yield point 220 MPa (32,000 lb/in²); elongation in 8 in, 30%; Young’s modulus 200 GPa (29×10^6 lb/in²).

Plain carbon steels are alloys of iron and carbon containing small amounts of manganese (up to 1.65%) and silicon (up to 0.50%) in addition to impurities of phosphorus and sulfur. Additions up to 0.30% copper may be made in order to improve corrosion resistance. The carbon content may range from 0.05% to 2%, although few alloys contain more than 1.0%, and the great bulk of steel tonnage contains from 0.08% to 0.20% and is used for structural applications. Medium-carbon steels contain around 0.40% carbon and are used for constructional purposes—tools, machine parts, etc. High-carbon steels have 0.75% carbon or more and may be used for wear and abrasion-resistance applications such as tools, dies, and rails. Strength and hardness increase in proportion to the carbon content while ductility decreases. Phosphorus has a significant hardening effect in low-carbon steels, while the other components have relatively minor effects within the limits they are found. It is difficult to generalize the properties of steels, however, since they can be greatly modified by cold working or heat treatment.

High-strength low-alloy steels are low-carbon steels (0.10% to 0.15%) to which alloying elements such as phosphorus, nickel, chromium, vanadium, and niobium have been added to obtain higher strength. This class of steel was developed primarily by the transportation industry to decrease

vehicle weight, but the steels are widely used. Since thinner sections are used, corrosion resistance is more important, and copper is added for this purpose.

Free-Machining Steels. Additions of manganese, phosphorus, and sulfur greatly improve the ease with which low-carbon steels are machined. The phosphorus hardens the ferrite, and the manganese and sulfur combine to form nonmetallic inclusions that help form and break up machining chips. The improvement in machinability is gained at some loss of mechanical properties, and these steels should be used for noncritical applications. Small amounts of lead also improve machining characteristics of steel by helping break up chips as well as providing a self-lubricating effect. Lead is more often added to higher-carbon steels where the effect on mechanical properties is less detrimental than that caused by sulfide inclusions.

Alloy Steels. When alloying ingredients (in addition to carbon) are added to iron to improve its mechanical properties, the product is known as an *alloy steel*. Heat treatment is a necessary part of the manufacture and use of alloy steels; only through proper quenching and tempering can the full beneficial effects of the alloys be obtained. The chief advantages obtained from the addition of alloys to steel are (1) to increase the depth of hardening on quenching, thus making it possible to produce more uniform properties throughout thick sections with a minimum of distortion, and (2) to form chemical compounds which when properly distributed develop desirable properties in the steel, that is, extreme hardness, corrosion or heat resistance, and high strength without excessive brittleness.

The most commonly used alloy steels have been classified by the American Iron and Steel Institute and the Society of Automotive Engineers and are identified by a nomenclature system that is partially descriptive of the composition. The system of steel designations and the approximate strengths of several alloy steels after specific heat treatments are available from various manufacturers. Mechanical properties of the alloy steels vary over a wide range depending on size, composition, and thermomechanical treatment.

Cast Iron. Iron ore is reduced to the metallic form in a blast furnace, yielding a product of molten iron saturated in carbon (about 4%). Most commonly, this “hot metal” is immediately processed to steel by a refining process without allowing it to solidify. Occasionally, it is cast into bars; this product is called *pig iron*. Cast iron is made by remelting pig iron and/or scrap steel in a cupola or electric furnace and casting it into molds to the desired shape of the finished part. Cast iron has a much higher carbon content than steel, usually between 2.5% and 3.75%.

Gray Cast Iron. In gray cast iron, the excess carbon beyond that soluble in iron is present as small flake-shaped particles of graphite. The flakes of graphite account for some of the unique properties of gray iron, in particular, its low tensile strength and ductility, its ability to absorb vibrational energy (damping capacity), and its excellent machinability. Cast iron is easy to cast because it has a lower melting point than steel, and the formation of the low-density graphite offsets solidification shrinkage so that minimal dimensional changes occur on freezing. Other elements in the composition of ordinary gray cast iron are important chiefly insofar as they affect the tendency of carbon to form as graphite rather than in chemical combination with the iron as iron carbide (Fe_3C). Silicon is most effective in promoting the formation of graphite. Slower cooling rates during freezing also favor the formation of graphite as well as increase the size of the flakes. Cooling rate also affects the mode of decomposition of the carbon retained in solution during freezing. Slow cooling favors complete precipitation as graphite, leaving a soft ferrite matrix, while fast cooling produces a stronger matrix containing Fe_3C (as pearlite). The tensile strength of gray cast iron typically ranges from 140 to 410 MPa (20,000 to 60,000 lb/in²). Corresponding compressive strengths are 575 to 1300 MPa (85,000 to 190,000 lb/in²). Young’s modulus may range from 70 to 150 GPa (10×10^6 to 20×10^6 lb/in²), depending on the microstructure.

White Cast Iron. Careful adjustment of composition and cooling rate can cause all the carbon in a cast iron to appear in the combined form as pearlite or free carbide. This structure is very hard and brittle and has few engineering applications beyond resistance to abrasion. This product does serve,

however, as an intermediate product in the production of malleable cast iron described in the following paragraph.

Malleable Cast Iron. By annealing white cast iron at about 950°C, the combined carbon will decompose to graphite. This graphite grows in a spheroidal shape rather than the flake-like shape that forms during the freezing of gray cast iron. Because of this difference in graphite shape, malleable iron is much tougher and stronger. If the castings are slowly cooled from the malleabilizing temperature, the matrix can be converted to ferrite, with all the carbon appearing as graphite; this is a very tough product. Faster cooling will yield a pearlitic matrix with greater strength and hardness. It is also possible to quench and temper malleable iron for optimum combinations of strength and toughness. By careful control of composition, the malleabilizing cycle can be carried out in 8 to 20 h.

Nodular Cast Iron. *Nodular cast iron* has the same carbon content as gray iron; however, the addition of a few hundredths of 1% of either magnesium or cerium causes the uncombined carbon to form spheroidal particles during solidification instead of graphite flakes. Strength properties comparable with those of steel may be achieved in the pearlitic iron. The softer ferritic and pearlitic as-cast irons exhibit considerable ductility, 10% elongation or more. As the hardness and strength are increased by appropriate heat treatment or the thickness of the casting decreased below approximately $\frac{1}{4}$ in, the ductility decreases. An austenitic form of nodular iron may be obtained by adding various amounts of silicon, nickel, manganese, and chromium. For many purposes, nodular iron exhibits properties superior to those of either gray or malleable cast iron.

Chilled Cast Iron. *Chilled cast iron* is made by pouring cast iron into a metallic mold which cools it rapidly near the surfaces of the casting, thus forming a wear-resisting skin of harder material than the body of the metal. The rapid cooling decreases the proportion of graphite and increases the combined carbon, resulting in the formation of white cast iron.

Alloy Cast Iron. *Alloy cast iron* contains specially added elements in sufficient amount to produce measurable modification of the physical properties. Silicon, manganese, sulfur, and phosphorus, in quantities normally obtained from raw materials, are not considered alloy additions. Up to about 4% silicon increases the strength of pure iron; greater content produces a matrix of dissolved silicon that is weak, hard, and brittle. Cast irons with 7% to 8% silicon are used for heat-resisting purposes and with 13% to 17% silicon form acid- and corrosion-resistant alloys, which, however, are extremely brittle. Manganese up to 1% has little effect on mechanical properties but tends to inhibit the harmful effects of sulfur. Nickel, chromium, molybdenum, vanadium, copper, and titanium are commonly used alloying elements. The methods of processing or of making the alloy additions to the iron influence the final properties of the metal; hence, a specified chemical analysis is not sufficient to obtain required qualities. Heat treatment is also employed on alloy irons to enhance the physical properties.

Density of Cast Iron. *Density of cast iron* varies considerably depending on the carbon content and the proportion of the carbon that is present as graphite. Using the density of pure iron, 7.86, as a reference, the density of cast iron may range from 7.60 for white cast iron to as low as 6.80 for gray cast iron.

Thermal Properties of Cast Iron. Thermal properties vary somewhat with the composition and the proportions of graphitic carbon. The average specific heat from 20 to 110°C is 0.119; thermal conductivity, 0.40 W/(cm³)(°C); coefficient of linear expansion, 0.000106/°C at 40°C.

Values of modulus of elasticity for ferrous metals may be assumed approximately as shown in Table 4-13. The values for all steels are fairly constant, whereas for cast irons the modulus increases somewhat with increased strength of material. Alloy steels have practically the same modulus as plain carbon steels unless large amounts, say, 10%, of alloying material are added; for large percentages of alloying elements, the modulus decreases slightly. The modulus of steels is not affected by heat treatment.

TABLE 4-13 Approximate Modulus of Elasticity for Ferrous Metals

Metal	Modulus in tension-compression, GPa (lb/in ² × 10 ⁻⁶)	Modulus in shear, GPa (lb/in ² × 10 ⁻⁶)
All steels	206 (30.0)	83 (12.0)
Wrought iron	186 (27.0)	75 (10.8)
Malleable cast iron	158 (23.0)	63 (9.2)
Gray cast iron, ASTM No. 20	103 (15.0)	41 (6.0)
Gray cast iron, ASTM No. 60	138 (20.0)	55 (8.0)

Heat Treatment of Steel. The properties of steels can be greatly modified by thermal treatments, which change the internal crystalline structure of the alloy. *Hardening* of steel is based on the fact that iron undergoes a change in crystal structure when heated above its “critical” temperature. Above this critical transformation temperature, the structure is called *austenite*, a phase capable of dissolving carbon up to 2%. Below the critical temperature, the steel transforms to *ferrite*, in which carbon is insoluble and precipitates as an iron carbide compound, Fe₃C (sometimes called *cementite*). If a steel is cooled rapidly from above the critical temperature, the carbon is unable to diffuse to form cementite, and the austenite transforms instead to an extremely hard metastable constituent called *martensite*, in which the carbon is held in supersaturation. The hardness of the martensite depends sensitively on the carbon content. Low-carbon steels (below about 0.20%) are seldom quenched, while steels above about 0.80% carbon are brittle and liable to crack on quenching. Plain carbon steels must be quenched at very fast rates in order to be hardened. Alloying elements can be added to decrease the necessary cooling rates to cause hardening; some alloy steels will harden when cooled in air from above the critical temperature. It should be noted, however, that it is the amount of carbon that primarily determines the properties of the alloy; the alloying elements serve to make the response to heat treatment possible.

Normalizing is a treatment in which the steel is heated over the critical temperature and allowed to cool in still air. The purpose of normalizing is to homogenize the steel. The carbon in the steel will appear as a fine lamellar product of cementite and ferrite called pearlite.

Annealing is similar to normalizing, except the steel is very slowly cooled from above the critical. The carbides are now coarsely divided and the steel is in its softest state, as may be desired for cold-forming or machining operations.

Process annealing is a treatment carried out below the critical temperature designed to recrystallize the ferrite following a cold-working operation. Metals become hardened and embrittled by plastic deformation, but the original state can be restored if the alloy is heated high enough to cause new strain-free grains to nucleate and replace the prior strained structure. This treatment is commonly applied as a final processing for low-carbon steels where ductility and toughness are important, or as an intermediate treatment for such products as wire that are formed by cold working.

Stress-relief annealing is a thermal treatment carried out at a still lower temperature. No structural changes take place, but its purpose is to reduce residual stresses that may have been introduced by previous nonuniform deformation or heating.

Tempering is a treatment that always follows a hardening (quenching) treatment. After hardening, steels are extremely hard, but relatively weak owing to their brittleness. When reheated to temperatures below the critical, the martensitic structure is gradually converted to a ferrite-carbide aggregate that optimizes strength and toughness. When steels are tempered at about 260°C, a particularly brittle configuration of precipitated carbides forms; steels should be tempered above or below this range. Another phenomenon causing embrittlement occurs in steels particularly containing chromium and manganese that are given a tempering cycle that includes holding at or cooling through temperatures around 567 to 621°C. Small molybdenum additions retard this effect, called *temper brittleness*. It is believed to be caused by a segregation of trace impurity elements to the grain boundaries.

Manganese Steels. Manganese is present in all steels as a scavenger for sulfur, an unavoidable impurity; otherwise, the sulfur would form a low-melting constituent containing FeS, and it would

be impossible to hot work the steel. The manganese content should be about 5 times the sulfur to provide protection against this "hot shortness." Beyond this amount, manganese increases the hardness of the steel and also has a strong effect on improving response to hardening treatment, but increases susceptibility to temper brittleness. Manganese can be specified up to 1.65% without the steel being classified as an alloy steel. The alloy containing 12% to 14% Mn and around 1% carbon is called *Hadfield's manganese steel*. This alloy can be quenched to retain the austenite phase and is quite tough in this condition. When deformed, this austenite transforms to martensite, which confers exceptional wear and abrasion resistance. Applications for this unique steel include railroad switches, crushing and grinding equipment, dipper bucket teeth, etc.

Vanadium Steels. In amounts up to 0.01%, vanadium has a powerful strengthening effect in microalloyed high-strength, low-alloy steels. In alloy steels, 0.1% to 0.2% vanadium is used as a deoxidizer and carbide-forming addition to promote fine-grained tough steels with deep hardening characteristics. Vanadium accentuates the benefits derived from other alloying elements such as manganese, chromium, or nickel, and it is used in a variety of quaternary alloys containing these elements. Vanadium in amounts of 0.15% to 2.50% is an important element in a large number of tool steels.

Silicon Steels. Silicon is present in most constructional steels in amounts up to 0.35% as a deoxidizer to enhance production of sound ingot structures. Silicon increases the hardenability of steel slightly and also acts as a solid solution hardener with little loss of ductility in amounts up to 2.5%. Silicon in amounts of about 4.5% is a major ingredient in electrical steel sheets. Silicon improves the magnetic properties of iron, but even more important, these steels can be fabricated to produce controlled grain size and orientation. Since permeability depends on crystal orientation, exceptionally small core losses are obtained by using grain-oriented silicon steel in motors and transformers. Alloys containing 12% to 14% Si are exceptionally resistant to corrosion by acids. This alloy is too brittle to be rolled or forged, but it can be cast and is widely used as drainpipe in laboratories and for containers of mineral acids.

Nickel Steels. Nickel is used as a ferrite strengthener and improves the toughness of steel, especially at low temperatures. Nickel also improves the hardenability and is particularly effective when used in combination with chromium. Nickel acts similarly to copper in improving corrosion resistance to atmospheric exposure. Certain iron-nickel alloys have particularly interesting properties and are used for special applications: *Invar* (36% Ni) has a very low temperature coefficient of expansion; *Platinite* (46% Ni) has the same expansion coefficient as platinum; and the 39% Ni alloy has the same coefficient as low-expansion glasses. These alloys are useful as gages, seals, etc. *Permalloys* (45% and 76% Ni) have exceptionally high permeability and are used in transformers, coils, relays, etc.

Chromium Steels. In constructional steels, chromium is used primarily as a hardener. It improves response to heat treatment and also forms a series of complex carbide compounds that improve wear and high-temperature properties. For these purposes, the amount of chromium used is less than 2%. Alloys containing around 5% Cr retain high hardness at elevated temperatures, and have applications as die steels and high-temperature processing equipment. Alloys containing more than 11% Cr have exceptional resistance to atmospheric corrosion and form the basis of the stainless steels.

Stainless Steels. Iron-base alloys containing between 11% and 30% chromium form a tenacious and highly protective chrome oxide layer that gives these alloys excellent corrosion-resistant properties. There are a great number of alloys that are generally referred to as *stainless steels*, and they fall into three general classifications.

Austenitic stainless steels contain usually 8% to 12% nickel, which stabilizes the austenitic phase. These are the most popular of the stainless steels. With 18% to 20% chromium, they have the best corrosion resistance and are very tough and can undergo severe forming operations. These alloys are susceptible to embrittlement when heated in the range of 593 to 816°C. At these temperatures,

carbides precipitate at the austenite grain boundaries, causing a local depletion of the chromium content in the adjacent region, so this region loses its corrosion resistance. Use of “extra low carbon” grades and grades containing stabilizing additions of strong carbide-forming elements such as niobium minimizes this problem. These alloys are also susceptible to stress corrosion in the presence of chloride environments.

Ferritic stainless steels are basically straight Fe-Cr alloys. Chromium in excess of 14% stabilizes the low-temperature ferrite phase all the way to the melting point. Since these alloys do not undergo a phase change, they cannot be hardened by heat treatment. They are the least expensive of the stainless alloys.

Martensitic stainless steels contain around 12% Cr. They are austenitic at elevated temperatures but ferritic at low; hence they can be hardened by heat treatment. To obtain a significant response to heat treatment, they have higher carbon contents than the other stainless alloys. Martensitic alloys are used for tools, machine parts, cutting instruments, and other applications requiring high strength. The austenitic alloys are nonmagnetic, but the ferritic and martensitic grades are ferromagnetic.

Heat-Resistant Alloys. Heat-resistant alloys are capable of continuous or intermittent service at temperatures in excess of 649°C. There are a great number of these alloys; they are best considered by class. *Iron-chromium alloys* contain between 10% and 30% chromium. The higher the chromium, the higher is the service temperature at which they can operate. They are relatively low-strength alloys and are used primarily for oxidation resistance. *Iron-chromium-nickel alloys* have chromium in excess of 18%, nickel in excess of 7%, and always more chromium than nickel. They are austenitic alloys and have better strength and ductility than the straight Fe-Cr alloys. They can be used in both oxidizing and reducing environments and in sulfur-bearing atmospheres. Iron-nickel-chromium alloys have more than 10% Cr and more than 25% Ni. These are also austenitic alloys and are capable of withstanding fluctuating temperatures in both oxidizing and reducing atmospheres. They are used extensively for furnace fixtures and components and parts subjected to nonuniform heating. They are also satisfactory for electric resistance-heating elements. *Nickel-base alloys* contain about 50% Ni, and also contain some molybdenum. They are more expensive than iron-base alloys, but have better high-temperature mechanical properties. *Cobalt-base alloys* contain about 50% cobalt and have especially good creep and stress-rupture properties. They are widely used for gas-turbine blades. Most of these alloys are available in both cast and wrought form; the castings usually have higher carbon contents and often small additions of silicon and/or manganese to improve casting properties.

4.4.3 Steel Strand and Rope

Iron and Steel Wire. Annealed wire of iron or very mild steel has a tensile strength in the range of 310 to 415 MPa (45,000 to 60,000 lb/in²); with increased carbon content, varying amounts of cold drawing, and various heat treatments, the tensile strength ranges all the way from the latter figures up to about 3450 MPa (500,000 lb/in²), but a figure of about 1725 MPa (250,000 lb/in²) represents the ordinary limit for wire for important structural purposes. For example, see the following paragraph on bridge wire. Wires of high carbon content can be tempered for special applications such as spring wire. The yield strength of cold-drawn steel wire is 65% to 80% of its ultimate strength. For examples showing the effects of drawing and carbon content on wire, see *Making, Shaping, and Treating of Steel*, U.S. Steel.

Galvanized-Steel Bridge Wire. The manufacture of high-strength bridge wire like that used for the cables and hangers of suspension bridges such as the San Francisco–Oakland Bay Bridge, the Mackinac Bridge in Michigan, and the Narrows Bridge in New York is an excellent example of careful control of processing to produce a quality material. The wire is a high-carbon product containing 0.75% to 0.85% carbon with maximum limits placed on potentially harmful impurities. Rolling temperatures are carefully specified, and the wire is subjected to a special heat treatment called *patenting*. The steel is transformed in a controlled-temperature molten lead bath to ensure an *optimal* microstructure. This is followed by cold drawing to a minimum tensile strength of 1550 MPa

(225,000 lb/in²) and a 4% elongation. The wire is given a heavy zinc coating to protect against corrosion. Joints or splices are made with cold-pressed sleeves which develop practically the full strength of the wire. Fatigue tests of galvanized bridge wire in reversed bending indicate that the endurance limit of the coated wire is only about 345 to 415 MPa (50,000 to 60,000 lb/in²).

Wire Rope. Wire rope is made of wires twisted together in certain typical constructions and may be either flat or round. Flat ropes consist of a number of strands of alternately right and left lay, sewed together with soft iron to form a band or belt; they are sometimes of advantage in mine hoists. Round ropes are composed of a number of wire strands twisted around a hemp core or around a wire strand or wire rope. The standard wire rope is made of six strands twisted around a hemp core, but for special purposes, four, five, seven, eight, nine, or any reasonable number of strands may be used. The hemp is usually saturated with a lubricant, which should be free from acids or corrosive substances; this provides little additional strength but acts as a cushion to preserve the shape of the rope and helps to lubricate the wires. The number of wires commonly used in the strands are 4, 7, 12, 19, 24, and 37, depending on the service for which the ropes are intended. When extra flexibility is required, the strands of a rope sometimes consist of ropes, which in turn are made of strands around a hemp core. Ordinarily, the wires are twisted into strands in the opposite direction to the twist of the strands in the rope. The makeup of standard hoisting rope is 6×19 ; extrapliable hoisting rope is 8×19 or 6×37 ; transmission or haulage rope is 6×7 ; hawsers and mooring lines are 6×12 or 6×19 or 6×24 or 6×37 , etc.; tiller or hand rope is 6×7 ; highway guard-rail strand is 3×7 ; galvanized mast-arm rope is 9×4 with a cotton center. The tensile strength of the wire ranges, in different grades, from 415 to 2415 MPa (60,000 to 350,000 lb/in²), depending on the material, diameter, and treatment. The maximum tensile efficiency of wire rope is 90%; the average is about 82.5%, being higher for 6×7 rope and lower for 6×37 construction. The apparent modulus of elasticity for steel cables in service may be assumed to be 62 to 83×10^6 kPa (9 to 12×10^6 lb/in²) of cable section. Grades of wire rope are (from historic origins) referred to as traction, mild plow, plow, improved plow, and extra improved plow steel. The most common finish for steel wire is "bright" or uncoated, but various coatings, particularly zinc (galvanized), are used.

4.4.4 Corrosion of Iron and Steel

Principles of Corrosion. Corrosion may take place by direct chemical attack or by electrochemical (galvanic) attack; the latter is by far the most common mechanism. When two dissimilar metals that are in electrical contact are connected by an electrolyte, an electromotive potential is developed, and a current flows. The magnitude of the current depends on the conductivity of the electrolyte, the presence of high-resistance "passivating" films on the electrode surfaces, the relative areas of electrodes, and the strength of the potential difference. The metal that serves as the anode undergoes oxidation and goes into solution (corrodes).

When different metals are ranked according to their tendency to go into solution, the galvanic series, or electromotive series, is obtained. Metals at the bottom will corrode when in contact with those at the top; the greater the separation, the greater the attack is likely to be. Table 4-14 is such a ranking, based on tests by the International Nickel Company, in which the electrolyte was seawater. The nature of the electrolyte may affect the order to some extent. It also should be recognized that very subtle differences in the nature of the metal may result in the formation of anode-cathode galvanic cells: slight differences in composition of the electrolyte at different locations on the metal surface, minor segregation of impurities in the metal, variations in the degree of cold deformation undergone by the metal, etc. It is possible for anode-cathode couples to exist very close to each other on a metal surface. The electrolyte is a solution of ions; a film of condensed moisture will serve.

Corrosion Prevention. An understanding of the mechanism of corrosion suggests possible ways of minimizing corrosion effects. Some of these include (1) avoidance of metal combinations that are not compatible, (2) electrical insulation between dissimilar metals that have to be used together, (3) use of a sacrificial anode placed in contact with a structure to be protected (this is an expensive technique but can be justified in order to protect such structures as buried pipelines and ship hulls),

TABLE 4-14 Galvanic Series of Alloys in Seawater

↑ Noble or cathodic	Platinum
	Gold
↓ Active or anodic	Graphite
	Titanium
	Silver
	[Chlorimet 3 (62 Ni, 18 Cr, 18 Mo)
	[Hastelloy C (62 Ni, 17 Cr, 15 Mo)
	[18-8 Mo stainless steel (passive)
	[18-8 stainless steel (passive)
	[Chromium stainless steel 11–30% Cr (passive)
	[Inconel (passive) (80 Ni, 13 Cr, 7 Fe)
	[Nickel (passive)
	Silver solder
	[Monel (70 Ni, 30 Cu)
	[Cupronickels (60–90 Cu, 40–10 Ni)
	[Bronzes (Cu–Sn)
	[Copper
	[Brasses (Cu–Zn)
	[Chlorimet 2 (66 Ni, 32 Mo, 1 Fe)
	[Hastelloy B (60 Ni, 30 Mo, 6 Fe, 1 Mn)
	[Inconel (active)
	[Nickel (active)
	Tin
	Lead
	Lead–tin solders
	[18-8 Mo stainless steel (active)
	[18-8 stainless steel (active)
	Ni-Resist (high Ni cast iron)
	Chromium stainless steel, 13% Cr (active)
	[Cast iron
	[Steel or iron
	2024 aluminum (4.5 Cu, 1.5 Mg, 0.6 Mn)
	Cadmium
	Commercially pure aluminum (1100)
	Zinc
	Magnesium and magnesium alloys

Note: Alloys will corrode in contact with those higher in the series. Brackets enclose alloys so similar that they can be used together safely.

Source: Fontana and Green, *Corrosion Engineering*, McGraw-Hill, New York.

(4) use of an impressed *emf* from an external power source to buck out the corrosion current (called *cathodic protection*), (5) avoiding the presence of an electrolyte—especially those with high conductivities, and (6) application of a protective coating to either the anode or the cathode. The problems of corrosion control are complex beyond these simple concepts, but since the use of protective coatings on iron and steel is extensive, this subject is treated in the following sections.

Protective Coatings. Protective coatings may be selected to be inert to the corrosive environment and insulate the base metal from exposure, or the coating may be selected to have reasonable resistance to attack but act sacrificially to protect the base metal. Protective coatings may be considered in four broad classes: paints, metal coatings, chemical coatings, and greases. Painting is commonly used for the protection of structural iron and steel but must be maintained by periodic renewal. Metal coatings take various ranks in protective effectiveness, depending on the metal used and its characteristics as a coating material. A wide variety of metals are used to coat steels: zinc, tin, copper, nickel,

chromium, cobalt, lead, cadmium, and aluminum; coatings of gold and silver are also used for decorative purposes. Coatings may be applied by these principal methods: hot dipping, cementation, spraying, electroplating, and vapor deposition. The latter may involve simply evaporation and condensation of the deposited metal or may include a chemical reaction between the vapor and the metal to be coated.

Zinc coatings are more widely used for the protection of structural iron and steel than coatings of any other type. The hot-dip process is the earliest type known and is very extensively used at the present time; two improvements, the Crapo process and the Herman, or "galvannealed," process, are used in galvanizing wire. The cementation, or sherardizing, process consists of heating the articles for several hours in a packing of zinc dust in a slowly rotating container. Electroplating is also employed, and heavier coatings can be obtained than are usual with the hot-dip process, but adherence is difficult to obtain, and this process is not often used. See ASTM specifications for zinc-coated iron and steel products.

Aluminum coatings are applied by a cementation process which is commercially known as *calorizing*. The articles to be coated are packed in a drum in a mixture of powdered aluminum, aluminum oxide, and a small amount of ammonium chloride. The articles are then slowly rotated and heated in an inert atmosphere, usually of hydrogen. Such coatings are very resistant to oxidation and sulfur attack at high temperatures. Aluminum coatings also can be applied by the hot-dipping method and then are heat-treated to improve the alloy bond. Aluminum also can be applied by spraying. Aluminum-coated steel is used extensively for oxidation protection, for example, for heat ducts and automobile mufflers. Aluminum-zinc coatings, applied by hot dipping, have been developed that combine the high-temperature protection of aluminum with the sacrificial protection of zinc.

Almost all *tin coatings* are now applied by electrolytic deposition methods. The accurate control obtained by electrolytic deposition is important because of the high cost of tin. Unlike zinc, tin is electropositive to iron. The coating must remain intact; once penetrated, corrosion of the iron will be accelerated. If a zinc coating is penetrated, the zinc will still sacrificially protect the adjacent exposed iron. Tin has good corrosion resistance, is nontoxic, readily bonds to steel, is easily soldered, and is extensively utilized by the container industry for food and other substances.

The objective of *lead coating* of steel is to obtain an inexpensive corrosion-resistant coating. Lead alone will not alloy with iron; so it is necessary to add *tin* to the lead to obtain a smooth, continuous, adherent coating. Originally, about 25% tin (called *terne metal*) was used, but the tin content has been reduced as the price of tin has increased. Since corrosion protection is less effective in this case *terne-coated steel* is not used extensively. Applications include uses where corrosion is not too critical or likely, such as gasoline tanks and roofing sheets, or where the lubricating properties of the soft lead surface help forming operations.

Metal-spray coatings are applied by passing metal wire through a specially constructed spray gun which melts and atomizes the metal to be used as coating. The surface to be sprayed must be roughened to afford good adhesion of the deposited metal. Nearly all the commonly used protective metals can be applied by spraying, and the process is especially useful for coating large members or repairing coatings on articles already in place. Sprayed coatings can also be applied that will resist wear and can be used to build up worn parts such as armature shafts and bearing surfaces or to apply copper coatings to carbon brushes and resistors.

Chromium coatings can be applied by cementation or electroplating. In electroplating, the best results are secured by first plating on a base coating of nickel or nickel copper to receive the chromium. The great hardness of chromium gives it important applications for protection against wear or abrasion; it will also take and retain a high polish. Very thin coatings have a tendency to be inefficient as a result of the presence of minute pinholes.

Electroplating is employed in the application of coatings of nickel, brass, copper, chromium, cadmium, cobalt, lead, and zinc. Only cadmium, chromium, and zinc are electronegative to iron. The other metals mentioned are employed because of their own corrosion-resistant properties and because they afford surface finishes having certain desirable characteristics.

Protective Paints. Protective paints are extensively employed to protect heavily exposed structures of iron and steel, such as bridges, tanks, and towers. The protection is not permanent but gradually wears

away under weather exposure and must be reviewed periodically. Various specially prepared paints are used for protecting the surface from dampness, oxidizing gases, and smoke. No one paint is suitable for all purposes but the choice depends on the nature of the corrosive influence present. Asphaltum and tar protect the surface by formation of an impervious film. A chemical protective action is exerted by paints containing linseed oil as the vehicle and red lead as the pigment; linseed oil absorbs oxygen from the atmosphere and forms a thick elastic covering, a formation hastened by adding salts of manganese or lead to the oil. All dryers, vehicles, and pigments used in paint must be inert to the steel; otherwise, corrosion will be hastened instead of prevented. Graphite- and aluminum-flake pigments give very impermeable films but do not show the inhibitive action of red lead or zinc when the films are scratched. Aluminum has the advantage of reflecting both infrared and ultraviolet rays of the sun; hence, it protects the vehicle from a source of deterioration and is used to paint gasoline-storage tanks to prevent excessive heating due to the sun's rays. A large number of new protective coatings have been developed recently from synthetic materials such as silicones, artificial rubbers, and phenolic plastics. Many of these are tightly adhering compounds in the form of paints or varnishes which offer rather good protection against a wide variety of chemical attacks. The majority of these new coatings, however, are sensitive to abrasion, and many of them must be baked on to secure full effectiveness.

Corrosion-Resistant Ferrous Alloys. Corrosion-resistant ferrous alloys such as rustless or stainless iron and steel have come into use for both structural and ornamental purposes but on account of their chromium and nickel contents are relatively expensive in comparison with the ordinary structural steels. Copper-bearing iron and steel, containing about 0.15% to 0.25% copper, are used extensively; the copper content tends to retard corrosion slightly but does not prevent it, and some protective coating is usually necessary. Some structural uses have been made of these steels without applying special protective coatings. A tightly adherent brown oxide surface film forms from weathering to serve as the future "protective coating."

Copperweld. A series of steel products, including wire, wire rope, bars, clamps, ground rods, and nails, that contain a copper-clad surface are made by the Copperweld process. The copper coating is intimately bonded to the steel by pouring a ring of molten copper about a heated steel billet fastened in the center of a refractory mold. The solidified composite ingot is then hot-rolled to bar stock and subsequently cold drawn to the various wire sizes. The thickness of the copper coating on wire is 10% to 12½% of the wire radius and produces a high-strength steel wire with a resistance to corrosion similar to that of a solid copper wire. Their increased electrical conductivity over that of a solid steel wire or rod makes the Copperweld products suitable for high-strength conductors, ground rods, aerial cable messengers, etc.

4.4.5 Nonferrous Metals and Alloys

Copper. Numerous commercial "coppers" are available. The standard product is *tough-pitch* copper, which contains about 0.04% oxygen. If it has been electrolytically refined, it is called *electrolytic tough pitch*. This copper cannot be heated in reducing atmospheres because the oxygen will react with hydrogen and severely embrittle the alloy. Various deoxidized varieties are made. When deoxidized with phosphorus, there is some loss of electrical conductivity depending on the amount of residual phosphorus and the extent to which other impurities are reduced and redissolve in the metal. As a general principle, alloying elements that dissolve in copper reduce conductivity sharply; those that are insoluble have little effect.

Copper castings are improved by using special deoxidizers such as Boroflux and silicocalcium copper alloy. By the use of these deoxidizers, the castings are improved structurally, and the electrical conductivity can be increased to about 80% to 90% of standard annealed copper. Boroflux is a mixture of boron suboxide, boric anhydride, magnesia, and magnesium; for data on its use, see publications of the General Electric Company.

Oxygen-free high-conductivity copper is deoxidized with carbon, and thus is free of residual oxide or deoxidizer. It is a more expensive product but does not suffer the potential embrittlement of

tough pitch and is capable of more severe cold-forming operations at the cost of a slight loss of electrical conductivity. Free-machining copper contains lead or tellurium that drops conductivity from 3% to 5%. Since copper is a very difficult material to machine, this may be a small sacrifice for certain applications. Small amounts of silver improve resistance to elevated-temperature softening with no loss of physical or mechanical properties.

Brass. Brasses are alloys of copper and zinc; commercial brasses contain from 5% to 45% zinc. A wide variety of properties are obtainable in the brasses. In general, the alloys have excellent corrosion resistance, good mechanical properties, colors ranging from red to gold to yellow to white, and are available in a wide variety of cast and wrought shapes. The alloy of 30% zinc has an optimum combination of strength and ductility. It is called “cartridge brass,” since an early application was drawing of cartridge shells. It is the most commonly used brass alloy.

Muntz metal contains nominally 40% zinc and is a two-phase alloy that is readily hot-worked in the high-temperature form and develops good strength when cooled. It is used for extruded shapes and for bolts, fasteners, and other high-strength applications. The properties of brass can be modified by small additions of numerous alloying elements; those commonly used include silicon, aluminum, manganese, iron, lead, tin, and nickel. The addition of 1% tin to cartridge brass results in an alloy called *Admiralty brass*, which has very good corrosion resistance and is extensively used in heat exchangers.

Brasses, especially the high zinc-bearing alloys, are subject to a corrosion phenomenon called *dezincification*. It involves a selective loss of zinc from the surface and the formation of a spongy copper layer accompanied by deterioration of mechanical properties. It is more likely to occur with the high-zinc brasses in contact with water containing dissolved CO_2 at elevated temperatures. Like many other metals, the brasses are susceptible to stress-corrosion cracking—an embrittlement due to the combined action of stress and a selective corrosive agent. In the case of brass, the particular agent responsible for stress-corrosion cracking is ammonia and its compounds. Brass products that might be exposed to such environments should be stress-relief annealed before being placed in service. For details on compositions and properties of brasses, see the appropriate ASTM specifications and the publications of brass producers.

Bronze, or Copper-Tin, Alloys. Bronze is an alloy consisting principally of copper and tin and sometimes small proportions of zinc, phosphorus, lead, manganese, silicon, aluminum, magnesium, etc. The useful range of composition is from 3% to 25% tin and 95% to 75% copper. Bronze castings have a tensile strength of 195 to 345 MPa (28,000 to 50,000 lb/in²), with a maximum at about 18% of tin content. The crushing strength ranges from about 290 MPa (42,000 lb/in²) for pure copper to 1035 MPa (150,000 lb/in²) with 25% tin content. *Cast bronzes* containing about 4% to 5% tin are the most ductile, elongating about 14% in 5 in. Gunmetal contains about 10% tin and is one of the strongest bronzes. Bell metal contains about 20% tin. *Copper-tin-zinc alloy* castings containing 75% to 85% copper, 17% to 5% zinc, and 8% to 10% tin have a tensile strength of 240 to 275 MPa (35,000 to 40,000 lb/in²), with 20% to 30% elongation. *Government bronze* contains 88% copper, 10% tin, and 2% zinc; it has a tensile strength of 205 to 240 MPa (30,000 to 35,000 lb/in²), yield strength of about 50% of the ultimate, and about 14% to 16% elongation in 2 in; the ductility is much increased by annealing for ½ h at 700 to 800°C, but the tensile strength is not materially affected. *Phosphor bronze* is made with phosphorus as a deoxidizer; for malleable products such as wire, the tin should not exceed 4% or 5%, and the phosphorus should not exceed 0.1%. *United States Navy bronze* contains 85% to 90% copper, 6% to 11% tin, and less than 4% zinc, 0.06% iron, 0.2% lead, and 0.5% phosphorus; the minimum tensile strength is 310 MPa (45,000 lb/in²), and elongation at least 20% in 2 in. *Lead bronzes* are used for bearing metals for heavy duty; an ordinary composition is 80% copper, 10% tin, and 10% lead, with less than 1% phosphorus. *Steam or valve bronze* contains approximately 85% copper, 6.5% tin, 1.5% lead, and 4% zinc; the tensile strength is 235 MPa (34,000 lb/in²), minimum, and elongation 22% minimum in 2 in (ASTM Specification B61). The bronzes have a great many industrial applications where their combination of tensile properties and corrosion resistance is especially useful.

Beryllium-Copper Alloys. Beryllium-copper alloys containing up to 2.75% beryllium can be produced in the form of sheet, rod, wire, and tube. The alloys can be hardened by a heat treatment consisting of quenching from a dull red heat, followed by reheating to a low temperature to hasten the precipitation of the hardening constituents. Depending somewhat on the heat treatment, the alloy of 2.0% to 2.25% beryllium has a tensile strength of 415 to 650 MPa (60,000 to 193,000 lb/in²), elongation 2.0% to 10.0% in 2 in, modulus of elasticity $125 \times \text{GPa}$ (18×10^6 lb/in²), and endurance limit of about 240 to 300 MPa (35,000 to 44,000 lb/in²). An outstanding quality of this alloy is its high endurance limit and corrosion resistance; it can be hardened by heat treatment to give great wear resistance and has high electrical conductivity. Typical applications include nonsparking tools for use where serious fire or explosion hazards exist and many electrical accessories such as contact clips and springs or instrument and relay parts. Beryllium is a toxic substance, and care should be taken to avoid ingesting airborne particles during such operations as machining and grinding. For details on properties and uses of beryllium bronzes, see publications of Kawecky Beryllco Industries, New York.

Nickel. Nickel is a brilliant metal which approaches silver in color. It is more malleable than soft steel and when rolled and annealed is somewhat stronger and almost as ductile. The tensile strength ranges from 415 MPa (60,000 lb/in²) for cast nickel to 795 MPa (115,000 lb/in²) for cold-rolled full-hard strip; yield strength 135 to 725 MPa (20,000 to 105,000 lb/in²); elongation in 2 in, 2% when full hard to about 50% when annealed; modulus in tension is about 205 GPa (30×10^6 lb/in²). Nickel takes a good polish and does not tarnish or corrode in dry air at ordinary temperatures. It has various industrial uses in sheets, pipes, tubes, rods, containers, and the like, where its corrosion resistance makes it especially suitable.

The greatest tonnage use of nickel is as an alloying element in steels, principally stainless and heat-resisting steels. There are also a variety of copper-nickel alloys whose main applications are based on their excellent corrosion resistance, for example, condenser tubes. Additions of aluminum and titanium to nickel-base alloys result in age-hardening characteristics, and they can be heat-treated to exceptionally high strengths that are retained to high temperatures. The International Nickel Company publishes an extensive list of bulletins describing the characteristics of nickel and nickel alloys.

Monel Metal. Monel metal is a silvery-white alloy containing approximately 66% to 68% nickel, 2% to 4% iron, 2% manganese, and the remainder copper. It can be cast, forged, rolled, drawn, welded, and brazed, and is easily machined. It melts at 1360°C and has a density of 8.80, coefficient of expansion of 14×10^{-6} per degree Celsius, thermal conductivity of 0.06 cgs unit, specific heat of 0.127 cal/(g)(°C), and modulus of 175 GPa (25×10^6 lb/in²). The tensile strength ranges from 450 MPa (65,000 lb/in²) for cast monel metal to 860 MPa (125,000 lb/in²) in cold-rolled full-hard strip; yield strength 175 to 725 MPa (25,000 to 115,000 lb/in²). It is highly resistant to corrosion and the action of seawater or mine waters. The industrial uses for it include many applications where its combination of physical properties and corrosion resistance gives it special advantages.

Magnesium Alloys. The outstanding feature of magnesium alloys is their light weight (specific gravity of about 1.8). Alloys containing thorium and rare-earth additions have been developed that retain good strength at temperatures between 260 and 371°C. The correspondingly high strength/weight ratio makes them particularly useful to the aircraft industry. Less exotic alloys, based mainly on alloying with aluminum (up to 10%) and zinc (up to 6%), still have excellent strengths and are heat-treatable. These alloys have many uses where low density is desired: portable tools, ladders, structural members for trucks and buses, housings, etc. Magnesium alloys are available as castings, forgings, extrusions, and rolled-mill products in a variety of shapes. Their thermal coefficient of expansion is about 0.000029/°C, and their melting point is about 620°C. Tensile strengths of castings range from 145 to 235 MPa (21,000 to 34,000 lb/in²), yield strengths from 62 to 150 MPa (9,000 to 22,000 lb/in²), and elongation from 1% to 10% in 2 in. Forged or extruded alloys have tensile strengths of 225 to 300 MPa (33,000 to 43,000 lb/in²), yield strengths 125 to 205 MPa (18,000 to 30,000 lb/in²), and elongations of 5% to 17% in 2 in. The Brinell hardness ranges from 35 to 78, and the endurance limit from 40 to 115 MPa (6,000 to 17,000 lb/in²) depending on the alloy and heat

treatment. Since magnesium is highly anodic to other common metals, care must be taken in designing with this metal. Protective coatings are used, and care must be taken to avoid forming galvanic couples. Finely divided magnesium will burn but massive sections are safely melted and welded.

Lead. Lead is a heavy, soft, malleable metal with a blue-gray color; it shows a metallic luster when freshly cut, but the surface is rapidly oxidized in moist air. It can be easily rolled into thin sheets and foil or extruded into pipes and cable sheaths but cannot be drawn into fine wire. Although in an ordinary tensile test lead may develop a tensile strength of 17 MPa (2400 lb/in²), it may creep at ordinary room temperatures at stresses as low as 0.34 MPa (50 lb/in²). Owing to this tendency to creep, it may fracture under long-continued load at stresses as low as 5.5 MPa (800 lb/in²), and the ordinary static tensile properties do not have much significance. The resistance of pure lead to corrosion makes it useful in the form of sheets, pipes, and cable coverings, and large quantities of lead are used in the manufacture of various alloys, particularly in alloys for bearings. Common alloys of lead for cable sheatings contain (approximately) 0.04% Cu, 0.75% Sb, or 0.03% Ca. The greatest use of metallic lead is in the manufacture of storage batteries.

Tin. Tin is a silvery-white, lustrous metal, very soft and malleable and of very low tensile strength. It has a density of about 7.3 and melts at 232°C. In ductility it equals soft steel. The tensile strength varies with the speed of testing. As a metal it has few uses except in sheets, but large quantities of it are used in various industrial alloys. Its chief uses are in tin- and terneplate, solder, babbitt and other bearing metals, brass, and bronze. Tin is very resistant to atmospheric corrosion, and water hardly affects it at all; however, it is electronegative to iron and therefore is not an efficient protective coating under atmospheric exposures.

Zinc. Zinc is a bluish-white metal which has a metallic luster on a new fracture. The density of cast zinc ranges from 7.04 to 7.16. At ordinary temperature it is brittle, but in the range of about 100 to 150°C it becomes malleable and can be rolled into sheets and drawn into wire. At 200°C, it becomes so brittle that it can be pulverized. The tensile strength of cast zinc ranges from about 55 to 95 MPa (8000 to 14,000 lb/in²) in an ordinary testing-machine test and that of drawn zinc from about 150 to 200 MPa (22,000 to 30,000 lb/in²); it has a poorly defined proportional limit of about 35 MPa (5000 lb/in²) and exhibits a certain amount of creep at room temperatures; hence, it may fracture in service under constant stresses below its testing-machine strength. It strongly resists atmospheric corrosion but is readily attacked by acids. The principal industrial uses for it are for galvanizing iron and steel, for plates and sheets for roofing and other applications, and for alloying with copper, tin, and other metals; very large quantities are used in the various types of brass. Next to galvanizing, the greatest use of zinc is in the production of die castings. Because of its moderate melting point, good mechanical properties, and especially because it does not attack steel melting pots and dies, it is the most popular die-casting material (although closely rivaled by aluminum). Zinc alloys for die casting contain some aluminum, copper, and magnesium; all ingredients must be very pure or the casting will have poor corrosion resistance and dimensional stability.

Titanium and Titanium Alloys. Titanium alloys are important industrially because of their high strength-weight ratio, particularly at temperatures up to 427°C. The density of the commercial titanium alloys ranges from 4.50 to 4.85 g/cm³, or approximately 70% greater than aluminum alloy and 40% less than steel. The purest titanium currently produced (99.9% Ti) is a soft, white metal. The mechanical strength increases rapidly, however, with an increase of the impurities present, particularly carbon, nitrogen, and oxygen. The commercially important titanium alloys, in addition to these impurities, contain small percentages (1% to 7%) of (1) chromium and iron, (2) manganese, and (3) combinations of aluminum, chromium, iron, manganese, molybdenum, tin, or vanadium. The thermal conductivity of the titanium alloys is low, about 15 W/m · K at 25°C, and the electrical resistivity is high, ranging from 54 μΩ · cm for the purest titanium to approximately 150 μΩ · cm for some of the alloys. The coefficient of thermal expansion of the titanium alloys varies from 2.8 to 3.6 × 10⁻⁶ per degree Celsius, and the melting-point range is from 1371 to 1704°C for the purest titanium. The tensile modulus of elasticity varies between 100 to 120 GPa (15 to 17 × 10⁶ lb/in²). The mechanical properties, at room temperature, for annealed commercial alloys range approximately as

follows: yield strength 760 to 965 MPa (110,000 to 140,000 lb/in²); ultimate strength 800 to 1100 MPa (116,000 to 160,000 lb/in²); elongation 5% to 18%; hardness 300 to 370 Brinell. On the basis of the strength-weight ratio many of the titanium alloys exhibit superior short-time tensile properties as compared with many of the stainless and heat-resistant alloys up to approximately 427°C. However, at the same stress and elevated temperature, the creep rate of the titanium alloys is generally higher than that of the heat-resistant alloys. Above about 482°C, the strength properties of titanium alloys decrease rapidly. The corrosion resistance of the titanium alloys in many media is excellent; for most purposes, it is the equivalent or superior to stainless steel.

Aluminum. Aluminum is an important commercial metal possessing some very unique properties. It is very light (density about 2.7) and some of its alloys are very strong, so its strength-weight ratio makes it very attractive for aeronautical uses and other applications in which weight saving is important. Aluminum, especially in the pure form, has very high electrical and thermal conductivities and is used as an electrical conductor in heat exchangers, etc. Aluminum has good corrosion resistance, is nontoxic, and has a pleasing silvery-white color; these properties make it attractive for applications in the food and container industry, architectural, and general structural fields.

Aluminum is very ductile and easily formed by casting and mechanical forming methods. Aluminum owes its good resistance to atmospheric corrosion to the formation of a tough, tenacious, highly insulating, thin oxide film, in spite of the fact that the metal itself is very anodic to other metals. In moist atmospheres, this protective oxide may not form, and some caution must be taken to maintain this film protection. Although aluminum can be joined by all welding processes, this same oxide film can interfere with the formation of good bonds during both fusion and resistance welding, and special fluxing and cleaning must accompany welding operations.

Commercially pure aluminum (99+%) is very weak and ductile: tensile strength of 90 MPa (13,000 lb/in²), yield strength of 34.5 MPa (5000 lb/in²), and shearing strength of 62 MPa (9500 lb/in²). Extrapure grades (electrical conductor grade) are 99.7+% pure, and are even weaker, but have better conductivity.

Heat Treatment of Aluminum Alloys. Alloys of the 1000, 3000, and 5000 series cannot be hardened by heat treatment. They can be hardened by cold working and are available in annealed (recrystallized) and cold-worked tempers. The 5000-series alloys are the strongest non-heat-treatable alloys and are frequently used where welding is to be employed, since welding will generally destroy the effects of hardening heat treatment. The remaining wrought alloys can be hardened by controlled precipitation of alloy phases. The precipitation is accomplished by first heating the alloy to dissolve the alloying elements, followed by quenching to retain the alloy in supersaturation. The alloys are then “aged” to develop a controlled size and distribution of precipitate that produces the desired level of hardening. Some alloys naturally age at room temperature; others must be artificially aged at elevated temperatures.

4.4.6 Stone, Brick, Concrete, and Glass Brick

Building Stone. Stone is any natural rock deposit or formation of igneous, sedimentary, and/or metamorphic origin, in either its original or its altered form. Building stone is the quarried product of such deposit or formation, which is suitable for structural and ornamental purposes. Igneous or volcanic rock, such as granite or basalt, is rock of plutonic or volcanic origin, formed from a fused condition and crystalline in structure. Sedimentary rock, such as limestone, dolomite, and sandstone, is formed by the deposition of particles from water and laminated in structure. Metamorphic rock, such as gneiss, marble, and slate, is rock formation which, in the natural ledge, has undergone marked change in microstructure or character due to heat, pressure, or moisture and therefore exists in form different from the original.

Portland Cement. *Portland cement* is produced by sintering a proportional mixture of lime and clay, which is subsequently ground with the addition of gypsum (to retard the rate of setting). The properties of the clay and limestone determine the principal characteristics: fineness, soundness,

time of set, and strength. Strength is measured from briquettes made of a mortar of 1 part cement to 3 parts sand, and measured under specified conditions. Minimum tensile strengths are 2 MPa (275 lb/in²) at 7 days, and 2.6 MPa (350 lb/in²) at 28 days.

Mortar. *Mortar* is a mixture of sand, screenings, or similar inert particles with cement and water, which has the capacity of hardening into a rocklike mass. The inert particles are usually less than ¼ in in size. The proportions of cement to sand range all the way from 1:0 to 1:4 for various purposes.

Concrete. *Concrete* is a mixture of crushed stone, gravel, or similar inert material with a mortar. The maximum size of inert particles is variable but usually less than 2 in. These inert constituents of mortar and concrete are known as the *aggregate*. In making good concrete, the properties of the aggregate are as important as those of the cement. The fine aggregates consist of sand, screenings, mine tailings, pulverized slag, etc., with particle sizes less than ¼ in; the coarse aggregates consist of crushed stone, gravel, cinders, slag, etc. Rubble concrete is made by embedding a considerable proportion of boulders or stone blocks in concrete. The proportions by volume of cement, sand, and coarse aggregate range all the way from 1:1:2 for high compressive strength to 1:4:8 for structures requiring mass more than strength. In general, the strength of concrete increases with the density and richness of mix (proportion of cement) but is decreased in proportion to the amount of mixing water that is added beyond that required to produce a plastic workable mixture. In controlling the quality of a concrete of given mix, the ratio of the volume of mixing water to the volume of cement (water-cement ratio) is often used as a criterion of the strength. For proper curing, the concrete should be kept moist for at least a week after placing, and care should be taken to prevent its freezing in cold weather during the early stages of curing. Freshly poured concrete gains strength very slowly in cold weather. Various admixtures are often added in small amounts to modify pouring characteristics and setting time as well as physical characteristics such as resistance to freezing and thawing cycles, wear, abrasion, and permeability.

For concrete of common proportions cured under good conditions, 25% to 40% of the 2-year strength is developed in 7 days, 50% to 65% in 1 month, and 70% to 90% in 6 months. The tensile strength of concrete is very low (about one-tenth its compressive strength), and hence in structural members the concrete is usually designed to resist the compressive stresses only, the tensile strength of the concrete being considered negligible. For flexural members, steel reinforcing bars are usually inserted on the tensile side of the beam to resist the tensile stresses.

4.5 WOOD PRODUCTS

By PHILIP MASON OPSAL

Wood Scientist—Consultant, Wood Science, LLC. This author's perception at the outset of the effort to construct this Section is that very few, if any, engineers of any specialty in the last 20 years have received any course work dealing with the subject of wood materials as a construction material. This is due to a number of reasons, including the evolution of course requirements at institution of higher learning to include newer and more modern construction materials, and the advent of the computer causing the need to use significant amounts of time for classes devoted to the teaching of engineers to be computer-wise, effectively providing the basic skills to accomplish all sorts of engineering design functions modeling, simulations, etc., significantly reducing time required for those tasks and increasing productivity for the professional engineer. It is thus that this Chapter is designed to be very basic in wood, not aiming at making professional electrical engineers into wood scientists, but rather to assist in the building of a knowledge base in wood to enable a better understanding of the material made in trees by natural forces. It is therefore purposeful that the bibliography has a considerable array of the old proven and very reliable textbooks of wood science/wood technology to allow the lessor experienced electrical engineer without such experience and/or even without any prior training that even opened up the subject of wood material. For those electrical engineers with

more experience and knowledge, the best way to consider proceeding with this chapter to increase and/or enhance the current knowledge base may well be to reference the more contemporary of the references shown and then pursue a course looking for keywords of phrases through the listed references that are to be found in each of those references following along possible avenues to larger more detailed and technical sources to the more current research.

4.5.1 Sources/Trees

The material known as *wood* has as its source *trees*. Natural in origin, the quality of this construction material is based primarily on the availability of the factors that contribute to tree growth, viz, sunlight, moisture, and nutrients. The best quality wood fiber results when these basic factors are at their optimum quantities. Wood materials of the best strength result from the selection of quality species, good forest management during the growing cycle, selective harvesting of only acceptable trees for a use such as utility poles, and then making certain that none of those hand-picked trees are damaged during any of the handling, hauling, and/or processing methods of operations. There are many species of trees present on the earth and on a broad basis are separated into *hardwoods* and *softwoods*; but these names do not truly reflect the relative “hardness” or “softness” of the wood resulting from the trees in either group inasmuch as balsa wood is in the hardwood category and is very lightweight and very weak wood, while a species such as *Douglas-fir*, a wood used in very large quantities as a strong structural member, is classified as a softwood. Generally, the hardwoods have leaves of fairly good size, such as maples, oaks, and elms, and are those trees which have a spreading configuration and are seen typically in yards, parks, and in some cities, lining the streets and avenues where in those locations and for such uses they appear as what are termed *ornamentals*. In hardwood forest stands, however, where, due to the density of the forest, with many trees per acre, natural pruning tends to occur and the tree trunks then grow more pole like with less branch remnants, allowing less deviated grain to form in the outer wood of the tree trunk as growth proceeds in height and circumference. Such was true of the American Chestnut, *Castanea dentata*, from which long tall poles were harvested and subsequently fabricated for use in utilities as supporting structures for conductor, crossarms, insulators, transformers, guys and anchors, regulators, OCRs, etc. Of course chestnut was prized and processed into wood products for many other applications as well. Unfortunately, the chestnut blight found its way from Europe and this organism severely devastated the majority of trees in the United States. Chestnut trees were known for their resistance to decay due to the heartwood section containing a high content of the organic chemicals called *tannins*.

Softwood are also known as *conifers* and most are evergreens keeping their leaves, which are usually “needle-like”, all year long (exceptions are Eastern larch and Western larch, respectively, *Larix laricina* and *Larix occidentalis*, which drop their leaves in the fall and grow new leaves each spring). The normal “form class” of the softwood trees is a long tapering trunk extending up to a crown of branches, which originate each year at the top of the tree in a “whorl” or sort of in a circle or sometimes a helical pattern around the circumference of the tree. Knots (earlier in the life of the tree its branches) cause the grain to deviate by the growth of the tree having to grow around the circular or elliptically shaped pattern of braches. It must be remembered that straight grain is the strongest while the greater the deviation of the grain is from straight the weaker the wood is. The configuration of knot whorls in clusters of closely adjacent knots can form a significant weakened section of a wood pole and, as well, weaken structural timbers such as crossarms and crossbraces. It is extremely important to require all wood products to be 100% inspected, examined, and assessed to ensure the receipt at destination of only quality wood capable of safely functioning to support the structure for which their use was designed by the professional electrical engineer.

4.5.2 Wood Structure

Gross wood structure may be used to differentiate between the hardwood and softwood classes and to identify species within each group. The cross section of a log shows several well-defined features from the outer bark, through the wood, to the central pith. The purpose of the bark is to protect the inner living tissues from injury. The inner portion of the bark is a conductive tissue that transports

foodstuffs from the leaves to the living cells. The wood portion of the tree has outer sapwood and inner heartwood regions, which often are distinguishable by a difference in color. The lighter-colored sapwood is a living tissue. The darker-colored heartwood consists of entirely dead cells and serves primarily for mechanical support in the tree. The heartwood contains deposits of gums, oils, and other organic infiltrations in the cells. These materials are called *extractives* and impart the darker color (ranging from light brown to black) to heartwood. Other differences include durability and permeability. Sapwood of all species is readily destroyed by insects and the decay fungi. The heartwoods of many species are also nondurable, but others are very durable (e.g., cypress, the cedars, and redwood). Sapwood is usually more permeable to liquids, owing largely to the absence of extractives. For this reason, sapwood is more easily treated with preservatives. Wood near the center of the tree is often characterized by fast growth and is termed *juvenile wood*. The properties of juvenile wood are inferior to those of normal heartwood. The strength properties of heartwood and sapwood are the same.

Annual Rings. In temperate zones, the tree increases in diameter and height by division of cells in a singular cell layer, called the *cambium*, capable of dividing and simultaneously supplying a new cell both in the direction of the bark and in the direction of the mass of the tree. The growth increment for each year is called the *annual ring*. The trees of North America have well-defined annual rings due to the production of cellular structure differing during the spurt of growth in the spring, when the tree growth surges and the wood cells produced by such fast growth are very thin-walled and are structurally weaker than those produced later in the growing season as the growth slows and the cells produced tend to be thicker-walled and thus are stronger structurally. These growth patterns have been termed *earlywood* (*Springwood*) and/or *latewood* (*Summerwood*) and show up as distinctive sections in the annual ring produced in each growing season. Because of this, the age of the tree can be determined by simply counting the rings beginning just inside the bark of the tree and continuing into the pith, the name given to the very center of each tree. (Note: Inasmuch as trees do not always grow in symmetry with purely concentric rings, the growth on two or more sides of the tree may have to be averaged.) Counting the rings and determining the percent of the latewood in the rings is often used as a tool in an attempt to roughly define the strength of wood to be used in a structural capacity. Tropical woods, producing growth nearly continuously, do not usually display seasonal growth rings.

Minute Wood Structure. Minute wood structure differs for hardwood and softwood species. The conifers are composed primarily of long hollow fibers oriented with their long axis parallel to the length of the tree. The ends of these fibers are tapered and the adjacent ends overlapping. The size, shape, and structure of these fibers vary considerably from one species to another, which accounts for much of the variation in properties of the respective wood. Given wood's *Orthotropic* nature, having three distinctly different axes, the longitudinal, the radial, and the tangential, the characteristics of each such as shrinkage are significantly different with a very small amount of shrinkage longitudinally followed by the radial and then by the tangential exhibiting the greatest amount, respectively less than 1% approximately 0.1% to 0.2%, radial 2% to 8%, and tangentially 4% to 14%. The individual fibers, primarily tracheids, are composed of multilayer cell wall enclosed within a central hollow void, much like a soda straw.

Chemical Composition. Chemically, wood consists of approximately 70% cellulose, 25% lignin, and about 5% extractives. The strength of wood may be attributed almost entirely to the cellulose and lignin present in the cell wall. The extractives do not contribute to the cell wall structure but do contribute to such properties as color, odor, taste, and resistance to decay.

Specific Gravity. Specific gravity is a measure of the amount of material contained in a piece of wood. It is calculated by dividing the weight of a given volume of wood by the weight of an equal volume of water. Specific gravity varies according to the amount of water present in wood. For this reason, the oven-dry weight of wood is usually used for reported values of specific gravity. The specific gravity of some commercially imported woods is listed in Table 4-15. For clear, straight-grained

TABLE 4-15 Specific Gravity and Shrinkage of Common Woods

Species	Average specific gravity*	Shrinkage, % [†]	
		Radial	Tangential
Douglas fir, various regions	0.43–0.48	3.6–5.0	6.2–7.8
White ash	0.60	4.8	7.8
Aspen	0.38	3.3	7.9
Yellow birch	0.55	7.2	9.2
White fir	0.37	3.2	7.1
Western red cedar	0.33	2.4	5.0
Northern white cedar	0.31	2.2	4.9
Western hemlock	0.42	4.3	7.9
Southern yellow pines	0.51–0.61	4.4–5.5	7.4–7.8
Tamarack	0.53	3.7	7.4
White oak species	0.63–0.68	4.1–5.5	7.2–10.8
Red oak species	0.59–0.69	4.0–5.5	8.2–10.6
Hickory species	0.69–0.75	7.0–7.8	10.0–12.6

*Weight oven-dry and volume at 12% moisture content.

[†]From green to oven-dry condition, based on green dimension.

Source: U.S. Forest Products Laboratory.

wood at a known moisture content, specific gravity is positively correlated with several important properties, including strength and stiffness in bending, tension, and compression. Approximate functions for predicting the mechanical properties of wood for known average and/or specific gravity ranges are given in the *Wood Handbook*. When wood contains natural growth characteristics and/or imperfections, the relationship between properties and specific gravity may be less pronounced due to the disruption of the structural continuity and/or integrity of straight-grained wood known to be the strongest.

4.5.3 Moisture in Wood

Wood is a hygroscopic material. Moisture in wood occurs in three forms: water vapor in airspaces in the cell cavities, capillary water in the cell cavities, and water molecules bound to the hydroxyl groups of the cellulose in the cell wall. In most end-use conditions, when wood is not in contact with water, nearly all the moisture present is bound water and is usually between 3% and 30% of the dry weight of the wood. Since this bound water tends to be at equilibrium with the vapor pressure of the surrounding atmosphere, the maximum amount of bound water in wood occurs in a saturated atmosphere. Any increase in moisture content above this maximum is due to capillary water, acquired from contact with liquid water.

The moisture content of wood is expressed as a percentage of the oven-dry weight of wood. It can be measured by weighing a wood sample before and after drying to constant weight at $103^{\circ}\text{C} \pm 3^{\circ}\text{C}$ (217.4°F) using the relationship:

$$\text{Moisture content, \%} = \frac{\text{moist weight} - \text{dry weight}}{\text{dry weight}} \times 100$$

When moist wood dries, the liquid water present in the cell capillaries evaporates before the bound water leaves the cell wall. The *fiber-saturation point* is defined as the moisture content of wood at that point at which the cell walls are saturated and there is no free water in the cell cavities. It is at this point that the moisture content is approximately 30%, varying somewhat among species.

Volumetric Changes. Below the fiber-saturation point, water that evaporates from wood results in a reduction in wood volume in the percentages cited earlier in the three directions, longitudinal, radial, and

tangential. The amount of volumetric change is positively related to the changes in moisture content and density and due to the orthotropic nature of the wood results in unequal shrinkage. In general, the shrinkage increases with density. Some representative shrinkage values are given Table 4-15. In round wood members, shrinkage results as the wood dries internal stresses develop until reaching the point that relief occurs manifested in the wood checks and splits taking place as to serve to eliminate the stresses. As wood poles dry out, shrinkage in circumference approximates 1% to 2% depending on size.

Wood Seasoning. Most wood products are dried prior to use to remove the large amount of moisture present in freshly cut wood. Wood that has been dried offers a number of advantages including reduced weight and shrinkage, an increase in strength, and durability compared to green wood. Drying may be accomplished by one of several procedures. Two of the most common are air drying and kiln drying. A number of defects may develop during drying if the process is not carefully controlled. These defects are the result of drying stresses due to unequal shrinkage. Most kiln-drying procedures include moisture-equalizing and conditioning treatments to improve moisture uniformity throughout the thickness of the wood product, and to relieve residual stresses. Improper drying may result in warping, checking, or more severe defects.

4.5.4 Thermal Properties of Wood

Temperature affects several properties of wood. As wood is heated, it expands. The coefficient of thermoexpansion for wood averages near 1.1×10^{-6} per degree Celsius for most native species. Wood is a good insulator and does not respond very fast to a change in environmental temperature. The coefficient of thermoconductivity for wood ranges from 0.4 to 0.7 Btu/(h)(°C) for a 1 ft² area 1 in in thickness at a moisture content of 12%. The thermoconductivity of wood increases with increasing specific gravity and moisture content.

4.5.5 Electrical Properties of Wood

Three important electrical properties of wood are resistivity, dielectric constant, and power factor. Wood is an excellent insulator. The resistivity of dry wood to the flow of direct current is high, approximately $3 \times 10^{17} \Omega \cdot \text{cm}/\text{cm}^3$ parallel to the grain. The presence of moisture lowers resistivity. The dielectric constant for wood determines the amount of stored electric potential energy when it is placed in a high-frequency alternating current. The dielectric constant for wood varies over a range from 2.0 for dry wood to 8 for wood above the fiber-saturation point. The dielectric constant is affected by density and grain direction. The power factor determines the amount of energy that is dissipated as heat when wood absorbs power in a high-frequency dielectric field. The power factor for wood is about 2% to 6% at low moisture contents for frequencies between 2 and 15 Hz.

4.5.6 Strength of Wood

Effect of Moisture on Strength. Clear wood generally increases in strength and stiffness as it dries below the fiber-saturation point. The change in strength resulting from a 1% change in moisture content, is approximately 4 for modulus of rupture, 2 for modulus of elasticity, and 5 for compression parallel to the grain.

For structural lumber, the increase in strength of the clear wood is partly offset by the development of seasoning defects such as checks and splits. For this reason, the properties in the green condition are generally used as the base for the development of design stresses for wood. For lumber that is nominally 5 cm (2 in) in thickness, the design stress is increased by up to 25% in bending, 20% in modulus of elasticity, and 37.5% in compression parallel to grain when the moisture content is at or less than 15%.

Effect of Temperature on Strength. In general, heating reduces and cooling increases the mechanical properties of wood. The change is immediate and irreversible for temperatures remaining above 66°C(150°F) for any appreciable period of time. The adverse effect of high temperature is more

pronounced at high moisture contents. For elevated temperatures below 66°C(150°F), the immediate loss of strength is recovered when the wood is cooled to ambient conditions. When wood is repeatedly exposed to high temperature, the adverse effect on properties is cumulative leading to creep and ultimate failure without any increase in loading.

Mechanical Properties. The mechanical properties of the commercially important woods of the United States have been evaluated in accordance with ASTM Standard D143, which specifies small, clear test specimens to eliminate the influence of naturally occurring physical defects in the wood. Tables 4-16 and 4-17 show some mechanical properties for wood in the green condition and at 12% moisture content, respectively. The green properties are obtained from specimens at essentially the same moisture content as in the living tree, well above the fiber-saturation point. The data in these tables include several of the more important hardwood and softwood species and the mechanical properties of each, which are likely to be uniquely important for specific uses encountered in electrical engineering applications. Adjustments to the values of strength determined for small, clear green test specimens are shown in ASTM Standard D245.

4.5.7 Decay and Preservatives

Decay and Its Prevention. At ordinary temperatures, wood is very stable and, unless attacked by living organisms, remains the same for centuries, either in air or under water. Fungi are the chief enemies of wood, and they thrive best with warmth and abundance of moisture and air, for example, in contact with the ground. Higher temperatures near the surface of the ground, together with adequate air and a greater prevalence of fungi, cause decay to progress faster near the ground line than at several feet below. Proper seasoning, together with protection against the entrance of moisture and impregnating with fungus-inhibiting compounds, which prevent fungi from feeding on the wood, is the best means of preservation. The heartwood of some species is resistant to decay whereas the sapwood of all species is nondurable to decay and insects and the preservative treatment, if done properly, substantially increases the safe service life of wood members.

Wood Preservatives. For a nominal cost, the service life of wood can be greatly increased by the use of preservative treatment. Creosote is extensively used for the protection of poles and crossarms. Southern yellow pine, because of its thick sapwood, requires a pressure treatment. Species with intermediate sapwood thickness such as Douglas-fir, lodgepole pine, and jack pine are treated by either pressure or nonpressure processes. Thin sapwood species such as western red cedar and larch are generally treated by nonpressure processes. The American Wood-Preservers' Association Standards are used to specify preservative chemicals and treatment methods for wood products. The AWPAs introduced the "Use-Category System" in 1999, where selection of products based on use and relative exposures to environmental conditions become the main bases of choice of products. After a period of 5 years of experience with the "Use-Category System", the 2004 AWPAs Standards have been completely rearranged to offer a more discerning, practical, and understood array of products fitted and custom-tailored by the industry to usage.

Wood preservatives fall into two main classes: (1) oil-borne preservatives and (2) water-borne metallic salts. The former may be further subdivided into (a) coal-tar creosote with and without the mixture of cheaper materials such as petroleum or coal tar and (b) solutions of toxic organic chemicals such as pentachlorophenol dissolved in petroleum oils. Oil-type preservatives are used extensively for products that are exposed to ground contact, whereby resistance to leaching is an important requirement of the preservative. These products include poles, crossties, crossarms, crossbraces, piling, bridge timbers, fence posts, and highway barrier posts. Water-borne preservatives are used mainly for the treatment of lumber. Wood treated with a water-borne preservative is clean, paintable, and odorless.

Creosote is a distillate of coal tar formed during the coking of coal during the steel-making process. Creosote has historically been a most important preservative significant in the preservation of wood members placed in contact with the ground, such as railroad ties, utility poles, piles, and timbers, for application to structures in coastal waters where significant destruction is inflicted on wharves and docks by marine organisms.

TABLE 4-16 Mechanical Properties of Various Woods in the Green Condition Grown in the United States

Species	Moisture content, %	Specific gravity*	Static bending		Compression parallel to grain maximum crushing strength, lb/in ²	Compression perpendicular to grain stress at proportional limit, lb/in ²	Tension perpendicular to grain maximum tensile strength, lb/in ²	Hardness [†]		Maximum shearing strength parallel to grain, lb/in ²
			Modulus of rupture, lb/in ²	Modulus of elasticity, 1,000 lb/in ²				End, lb	Side, lb	
Ash, black	85	0.45	6,000	1,040	2,300	350	490	590	520	860
Ash, white	42	0.55	9,600	1,460	3,990	670	590	1,010	960	670
Aspen	94	0.35	5,100	860	2,140	180	230	280	300	660
Basswood	105	0.32	5,000	1,040	2,220	170	280	290	250	600
Beech	54	0.56	8,600	1,380	3,550	540	720	970	850	1,290
Birch, yellow	67	0.55	8,300	1,500	3,380	430	430	810	780	1,110
Cottonwood, eastern	111	0.37	5,300	1,010	2,280	200	410	380	340	680
Elm, American	89	0.46	7,200	1,110	2,910	360	590	680	620	1,000
Elm, slippery	85	0.48	8,000	1,230	3,320	420	640	750	660	1,110
Hickory, shagbark	60	0.64	11,000	1,570	4,580	840	770	1,640	1,570	1,520
Locust, black	40	0.66	13,800	1,850	6,800	1,160	560	670	590	1,760
Maple, silver	66	0.44	5,800	940	2,490	370	750	1,070	970	1,050
Maple, sugar	58	0.56	9,400	1,550	4,020	640	770	1,060	1,000	1,210
Oak, red	80	0.56	8,300	1,350	3,440	610	770	1,120	1,060	1,250
Oak, white	68	0.60	8,300	1,250	3,560	670	540	670	600	990
Sweetgum	115	0.46	7,100	1,200	3,040	370	630	700	610	1,000
Sycamore	83	0.46	6,500	1,060	2,920	360	510	480	440	790
Yellow poplar	83	0.40	6,000	1,220	2,660	270	300	440	390	810
Baldcypress	91	0.42	6,600	1,180	3,580	400				

TABLE 4-16 Mechanical Properties of Various Woods in the Green Condition Grown in the United States (*Continued*)

Species	Moisture content, %	Static bending		Compression parallel to grain maximum crushing strength, lb/in ²	Compression perpendicular to grain stress at proportional limit, lb/in ²	Tension perpendicular to grain maximum tensile strength, lb/in ²	Hardness [†]		Maximum shearing strength parallel to grain, lb/in ²
		Modulus of rupture, lb/in ²	Modulus of elasticity, 1,000 lb/in ²				End, lb	Side, lb	
Cedar, northern white	55	4,200	640	1,990	230	240	320	230	620
Cedar, Port Orford	43	6,200	1,420	3,130	280	180	460	400	830
Cedar, western red	37	5,100	920	2,750	270	230	430	270	710
Douglas-fir, coast [‡]	38	7,700	1,560	3,780	380	300	570	500	900
Fir, white	110	5,900	1,160	2,900	280	300	410	340	760
Hemlock, western	77	6,600	1,310	3,360	280	290	500	410	860
Larch, western	58	7,700	1,460	3,760	400	330	580	510	870
Pine, lodgepole	65	5,500	1,080	2,610	250	220	320	330	680
Pine, ponderosa	91	5,100	1,000	1,940	280	310	310	320	700
Pine, loblolly	81	7,300	1,410	3,490	390	260	420	450	850
Pine, longleaf	62	8,700	1,600	4,300	480	330	550	590	1,040
Pine, shortleaf	81	7,300	1,390	3,430	350	320	410	440	850
Pine, western white	54	5,200	1,170	2,650	240	260	310	310	640
Spruce, Engelmann	80	4,500	960	2,190	220	240	310	260	590
Spruce, Sitka	42	5,700	1,230	2,670	280	250	430	350	760

Note: 1 lb/in² = 6.895 kPa; 1 lb = 0.4536 kg.

^{*}Specific gravity based on green volume and oven-dry weight.

[†]Load required to embed a 0.444-in ball to half its diameter.

[‡]Coast Douglas-fir is defined as that coming from counties in Oregon and Washington west of the summit of the Cascade Mountains. For Douglas-fir from other sources, see Western Wood Density Survey, U.S. Forest Service Res. Paper FPL 27.

TABLE 4-17 Mechanical Properties of Various Woods in the Air-Dry Condition Grown in the United States

Species	Moisture content, %	Specific gravity*	Static bending		Compression parallel to grain maximum crushing strength, lb/in ²	Compression perpendicular to grain stress at proportional limit, lb/in ²	Tension perpendicular to grain maximum tensile strength, lb/in ²	Hardness [†]		Maximum shearing strength parallel to grain, lb/in ²
			Modulus of rupture, lb/in ²	Modulus of elasticity, 1,000 lb/in ²				End, lb	Side, lb	
Ash, black	12	0.49	12,600	1,600	5,970	760	700	1,150	850	1,570
Ash, white	12	0.60	15,400	1,770	7,410	1,160	940	1,720	1,320	1,160
Aspen	12	0.38	8,400	1,180	4,250	370	260	510	350	850
Basswood	12	0.37	8,700	1,460	4,730	370	350	520	410	990
Beech	12	0.64	14,900	1,720	7,300	1,010	1,010	1,590	1,300	2,010
Birch, yellow	12	0.62	16,600	2,010	8,170	970	920	1,480	1,260	1,880
Cottonwood, eastern	12	0.40	8,500	1,370	4,910	380	580	580	430	930
Elm, American	12	0.50	11,800	1,340	5,520	690	660	1,110	830	1,510
Elm, slippery	12	0.53	13,000	1,490	6,360	820	530	1,120	860	1,630
Hickory shagbark	12	0.72	20,200	2,160	9,210	1,760				2,430
Locust black	12	0.69	19,400	2,050	10,180	1,830	640	1,580	1,700	2,480
Maple, silver	12	0.47	8,900	1,140	5,220	740	500	1,140	700	1,480
Maple, sugar	12	0.63	15,800	1,830	7,830	1,470		1,840	1,450	2,330
Oak, red	12	0.63	14,300	1,820	6,760	1,010	800	1,580	1,290	1,780
Oak, white	12	0.68	15,200	1,780	7,440	1,070	800	1,520	1,360	2,000
Sweetgum	12	0.52	12,500	1,640	6,320	620	760	1,080	850	1,600
Sycamore	12	0.49	10,000	1,420	5,380	700	720	920	770	1,470
Yellow poplar	12	0.42	10,100	1,580	5,540	500	540	670	540	1,190

TABLE 4-17 Mechanical Properties of Various Woods in the Air-Dry Condition Grown in the United States (*Continued*)

Species	Moisture content, %	Static bending		Compression parallel to grain maximum crushing strength, lb/in ²	Compression perpendicular to grain stress at proportional limit, lb/in ²	Tension perpendicular to grain maximum tensile strength, lb/in ²	Hardness [†]		Maximum shearing strength parallel to grain, lb/in ²
		Modulus of rupture, lb/in ²	Modulus of elasticity, 1,000 lb/in ²				End, lb	Side, lb	
Baldcypress	12	10,600	1,440	6,360	730	270	660	510	1,000
Cedar, northern white	12	6,500	800	3,960	310	240	450	320	850
Cedar, Port Orford	12	11,300	1,730	6,470	620	400	730	560	1,080
Cedar, western red	12	7,700	1,120	5,020	490	220	660	350	860
Douglas-fir, coast [‡]	12	12,400	1,950	7,240	800	340	900	710	1,130
Fir, white	12	9,800	1,490	5,810	530	300	780	480	1,100
Hemlock, western	12	11,300	1,640	7,110	550	340	900	540	1,250
Larch, western	12	13,100	1,870	7,640	930	430	1,120	830	1,360
Pine, lodgepole	12	9,400	1,340	5,370	610	290	530	480	880
Pine, ponderosa	12	9,400	1,290	5,320	580	420	570	460	1,130
Pine, loblolly	12	12,800	1,800	7,080	800	470	750	690	1,370
Pine, longleaf	12	14,700	1,990	8,440	960	470	920	870	1,500
Pine, shortleaf	12	12,800	1,760	7,070	810	470	750	690	1,310
Pine, western white	12	9,500	1,510	5,620	440		440	370	850
Spruce, Engelmann	12	8,700	1,280	4,770	470	350	560	350	1,030
Spruce, Sitka	12	10,200	1,570	5,610	580	370	760	510	1,150

Note: 1 lb/in² = 6.895 kPa; 1 lb = 0.4536 kg.

^{*}Specific gravity based on green volume and oven-dry weight.

[†]Load required to embed a 0.444-in ball to half its diameter.

[‡]Coast Douglas-fir is defined as that coming from counties in Oregon and Washington west of the summit of the Cascade Mountains. For Douglas-fir from other sources, see Western Wood Density Survey, U.S. Forest Service Res. Paper FPL 27.

Pentachlorophenol, appearing in crystalline form much like sugar and/or table salt must be dissolved in aromatic-type petroleum oils for best solubility to accomplish movement into the wood cells during the treating process. Low-boiling solvents like mineral spirits are used as a carrier for penta when cleanliness is required for products such as millwork where no contact with the ground is anticipated. Water repellents are added to millwork treatments to both minimize dimensional changes as well as to provide greater stability and permanence to the treated products. Other oil-borne preservatives such as copper naphthenate, copper-8-quinolinolate, tri-butyltin oxide, and other recent additional are commercially in use.

Water-borne preservatives are generally mixtures of several inorganic salts, the most important of which are salts of copper, chromium arsenic and zinc. Boron is an inorganic water becoming more widely used some of these preservatives give good protection to wood exposed to wet conditions while others are not recommended for such use. Wood treated with water-borne preservatives is clear and paintable after drying to below 25% moisture content.

Several supplemental wood preservatives are used to bolster the original wood preservatives of in-service wood poles, which over time have changed due to leaching and oxidation and thus no longer are protecting those poles as occurred during the earlier years in service. These supplemental preservatives come in the form of (1) bandages containing grease formulations for exterior applications, (2) liquids containing common preservatives like creosote, penta-in-oil, and sodium flouride to treat internal decay, and (3) another liquid for the same purpose which on contact with water changes form into a vapor (gas) becoming a *fumigant* and moving both up-and downward in the wood cells effectively killing decay present and offering lasting protection for extended periods of time.

Paints, varnishes, and stains are used for decorative effects, but they also afford surface protection by retarding moisture changes and thus decreasing checking, warping, and weathering. Such protection is only superficial and they are not wood preservatives.

Fire-retardant chemicals such as ammonium phosphate and sulfate and salts of zinc and boron are used to decrease the flammability of wood. Some fire-retardant formulations may give protection against decay.

Methods of Treating Wood. The methods of preservative treatment are divided into two categories, *pressure* and *nonpressure*. Pressure methods are very effective in the treating of difficult to treat woods such as Douglas-fir, and the processing usually takes much less time if the seasoning does not need to be accomplished in the cylinder than the nonpressure processes, which rely on vacuum, diffusion, and/or temperature differentials to treat the wood. The pressure is conducted in an air-tight cylinder with the preservative liquids being forced into the products, while the nonpressure methods such as dipping, soaking, brushing, and/or spraying are less effective and are not recommended for products requiring trouble-free long service lives or installation into ground exposures. The *vacuum process* can achieve better results and the *thermal process* is capable of treating wood poles for specifications requiring adequate retention and penetration into the wood, sufficient to protect wood for inground installation. The thermal process (formerly the "hot-cold" bath process) accomplishes the required penetration and retention of preservative by first covering the wood with a "hot" liquid at about 112.8°C (23°F), increasing the temperature of the air in the wood cells causing expansion, and then allowing the preservative to either cool down or pumping the hot oil out of the tank and pumping relatively cold preservative into the tank at about 66°C (150°F), which effectively cools the wood cells and the air to contract and form a vacuum pulling the preservative into the cells.

There are several modifications of the pressure process. The full-cell process is used for the treatment of marine piling, which requires high retention of creosote for protection against wood-boring animals. The process is also used commonly in the treatment of lumber with water-borne preservatives. An initial vacuum removes the air from the cell lumens providing maximum penetration and retention into those spaces and the cell walls. Much wood for land use is treated with oil-type preservatives by one of the so-called empty-cell methods, whereby it is possible to increase the depth of penetration obtained with a limited retention of preservative. In the Rueping process, air is first injected to create within the wood a pressure greater than atmospheric. The cylinder is filled with preservative in such a way that the injected air is trapped in the wood. The pressure is then increased to force preservative into the wood. After the pressure is released and the cylinder

drained, the compressed air in the wood expands to expel some of the preservative. The recovered preservative is called *kickback*. The Lowry process differs from the Rueping process in that no initial air pressure is applied. In this process, the air normally present in the cells is compressed during the pressure cycle and produces some kickback when pressure is released.

The conditioning of the wood prior to treatment is an important step. Air seasoning, kiln drying, and various processes of cylinder conditioning are employed. The latter include steaming plus vacuum, boiling in oil under vacuum, and vapor drying, in which green wood is surrounded by hot vapors of distillates of coal tar or petroleum.

When oil preservatives are applied by simple soaking methods, the wood should be well-seasoned in order to provide airspaces sans water into which the oil may move. Oil preservatives of low viscosity are preferable. The results attainable vary greatly with the species of wood.

Diffusion methods depend on the diffusion of water-soluble chemicals into the moisture present in green wood. Here again, the species of wood is an important factor, but the results are affected by other factors such as the nature of the chemical, the concentration of the solution, and the duration of the soaking period.

Applications of Preservative Treatment. Preservative treatments are applied to many wood products including poles, crossties, lumber, structural timbers such as crossarms and crossbraces, fence posts, and piling.

Advantages of Preservative Treatment. In addition to the conservation of a natural resource, preservative treatment results in economic savings due to increased service life and reduced maintenance costs. This has been recognized for many years by railroad companies, utility companies, and other large users of wood products. Because of demonstrated savings, practically all crossties and poles are now given a preservative treatment before installation. There has been a gradual increase in the volume of lumber treated annually, due to more widespread knowledge of the need for such treatment when the wood is to be used under conditions favorable to attack by decay or insects. For best performance, it is desirable that all machining operations be completed before treatment.

Strength of Treated Lumber. The effect of a preservative such as creosote or pentachlorophenol, in and of itself, on the strength of treated lumber appears to be negligible. It may be necessary, however, in establishing design stress values, to take into account possible reductions in strength that may result from temperatures or pressures used in the conditioning or treating processes. Results of tests of treated wood show reductions of stress in extreme fiber in bending and compression perpendicular to grain, ranging from a few percent up to 25%, depending on the processes used. Compression parallel to grain is affected less and modulus of elasticity very little. The effect on resistance to horizontal shear can be estimated by inspection for shakes and checks after treatment. Strength reductions for wood poles agreed on in formulating fiber-stress recommendations in American Standard Specifications and Dimensions for Wood Poles, ANSI 05.1, range from 0% to 15% in various species, depending on the conditioning and treating processes. Treating conditions specified by the American Wood-Preservers' Association should never be exceeded. Reductions of strength can be minimized by restricting temperatures, heating periods, and pressures as much as is consistent with obtaining the absorption and penetration required for proper treatment.

Effect of Preservative Treatment on Electrical Resistivity. The electrical resistivity of wood depends on its moisture content to a much greater degree than any other single variable. Oven-dry wood is an excellent insulator, but as the wood absorbs moisture, its resistivity decreases rapidly. Wood in normal use, however, where its moisture content may range from about 6% to 14%, is still a good enough insulator for many electrical applications.

When wood has been treated with salts for preservative or fire-retardant purposes, its electrical resistivity may be markedly reduced. The effect of such salt treatment is small when the wood moisture is below about 8% but increases rapidly as the moisture content exceeds about 10%. Treatment with creosote or pentachlorophenol has practically no effect on the resistivity of wood, just as long

as no excess water is the treating solution. The resistivity of wood decreases by about a factor of 2 for each increase of 10°C in the temperature and is about half as great for current flow along the grain as across the grain.

4.5.8 American Lumber Standards

Voluntary Product Standard PS 20-99, American softwood Lumber Standard is a voluntary standard of manufacturers, distributors, and users promulgated in cooperation with the U.S. Department of Commerce. It provides for use classifications of (1) yard lumber, (2) structural lumber, and (3) factory and shop lumber. Different grading rules apply to each class. Size standards and generalized grade descriptions are part of PS 20-99, but details of grading rules are left to the organized agencies of the lumber manufacturing industry. The grades and working stresses for structural lumber are referred by PS 20-99 to the authority of ASTM D245, Methods for Establishing Structural Grades of Lumber, or D2018, Recommended for Determining Design Stresses for Load-Sharing Lumber Members.

Standard Commercial Names. Standard commercial names of the most commonly used structural softwood from ASTM D1165, Standard Nomenclature of Domestic Hardwood and Softwoods, are as follows:

Cedar	Pine
Alaska cedar	Jack pine
Port Orford cedar	Lodgepole pine
Western red cedar	Norway pine
Fir	Ponderosa pine
Douglas-fir	Southern yellow pine
White fir	Redwood
Hemlock	Spruce
Eastern hemlock	Eastern spruce
Western hemlock	Engelmann spruce
Larch, Western	Sitka spruce

Standard Structural Grades. Detailed descriptions of the standard structural grades are published and promulgated in the grading rule books of the organized regional agencies of the lumber manufacturing industry. These are subject to review for compliance with the general requirements of PS 20-99, American softwood Lumber Standard. The principal-use classes of structural lumber are: (1) *joists and planks*, pieces of rectangular cross section 5 to 10 cm (2 to 4 in) thick and 10 cm (4 in) or more wide (nominal dimensions), graded primarily for bending strength edgewise or flatwise, (2) *beams and stringers*, pieces of rectangular cross section 12.7 by 20.3 cm (5 by 8 in) (nominal dimensions) and up, graded for strength in bending when loaded on the narrow face, and (3) *posts and timbers*, pieces of square or nearly square cross section, 12.7 by 12.7 cm (5 by 5 in) (nominal dimensions) and larger, graded primarily for use as posts and columns.

Working Stresses. Working stresses recommended by the lumber industry for their structural grades are found with the detailed grade descriptions in the grading rule books of the organized regional agencies of the industry. A complete listing of all structural grades and their working stresses is found in the *National Design Specification for Wood Construction*, published by ANSI/AF&PA Assn. Values for a few typical grades are shown in Table 4-18. Working stresses vary according to the grades and sizes of lumber and their condition with respect to moisture content. Stresses are adjustable also for duration of load and for special conditions such as extreme temperature. Stress increases are provided for “load-sharing/repetitive members” in which the safety of the structure

TABLE 4-18 Design Values for Visually Graded Timbers (5" × 5" and larger)*

USE WITH TABLE 4D ADJUSTMENT FACTORS

Species and commercial grade	Size classification	Design values in pounds per square inch (psi)					Modulus of Elasticity E	Grading Rules Agency
		Bending F _b	Tension parallel to grain F _t	Shear parallel to grain F _v	Compression perpendicular to grain F _{cl}	Compression parallel to grain F _c		
DOUGLAS FIR-LARCH								
Dense Select Structural	Beams and Stringers	1900	1100	170	730	1300	1,700,000	West Coast Lumber Inspection Bureau
Select Structural		1600	950	170	625	1100	1,600,000	
Dense No. 1		1550	775	170	730	1100	1,700,000	
No. 1		1350	650	170	625	925	1,600,000	
No. 2		875	425	170	625	600	1,300,000	
Dense Select Structural	Posts and Timbers	1750	1150	170	730	1350	1,700,000	
Select Structural		1500	1000	170	625	1150	1,600,000	
Dense No. 1		1400	950	170	730	1200	1,700,000	
No. 1		1200	825	170	625	1000	1,600,000	
No. 2		750	475	170	625	700	1,300,000	
(Wet Service Conditions)								
SOUTHERN PINE								
Dense Select Structural	5" × 5" & larger	1750	1200	165	440	1100	1,600,000	Southern Pine Inspection Bureau
Select Structural		1500	1000	165	375	950	1,500,000	
No. 1 Dense		1550	1050	165	440	975	1,600,000	
No. 1		1350	900	165	375	825	1,500,000	
No. 2 Dense		975	650	165	440	625	1,300,000	
No. 2		850	550	165	375	525	1,200,000	
Dense Structural 86		2100	1400	165	440	1300	1,600,000	
Dense Structural 72		1750	1200	165	440	1100	1,600,000	
Dense Structural 65		1600	1050	165	440	1000	1,600,000	

Note: 1 lb/in² = 6.895 kPa.

***LUMBER DIMENSIONS.** Tabulated design values are applicable to lumber that will be used under dry conditions such as in most covered structures. For 5" and thicker lumber, the GREEN dressed sizes shall be permitted to be used (see Table 1A) because design values have been adjusted to compensate for any loss in size by shrinkage which may occur. (Tabulated design values are for normal load duration and dry service conditions, unless specified otherwise. See NDS 4.3 for a comprehensive description of design value adjustment factors.)

Source: Compiled from *National Design Specification for Wood Construction* ANSI/APSP ASSN.-1

depends upon the strength of the assemblage of members rather than upon the lowest strength value for any single member. These stress modifications are described in ASTM standards.

Allowable working stresses for the structural grades of lumber are also a part of certain use specifications, such as the Minimum Property Standards of the Federal Housing Administration, the *American Railway Engineering Association Manual*, and various local or regional building codes. These allowable values may or may not coincide with the lumber industry stress recommendations for the same species and grade.

Wood-Base Panel Materials. Included in this category are insulating board, hardboard, particle board, waferboard, plywood, and several engineered-wood products. Plywood, normally fabricated by bonding an odd number of layers of veneers together with the grain direction in adjacent piles at right angles to each other, is more dimensionally stable and more uniform in strength in the plane of the sheet than wood. Qualities of glue line and veneer permitted are set by the various commercial standards for plywood and determine the grades under which plywood is sold. In general, glue-line quality determines whether plywood is classed as being suitable for interior or exterior use.

U.S. Product Standard PS1-83 covers the basic specifications for the manufacture of construction plywood. Decorative hardwood plywood is described by U.S. Product Standard PS51(5.2). Plywood manufactured according to this standard will carry a grade trademark of a qualified testing agency. Testing is conducted under PS2-92 and ASTM D1037.

Insulation boards and hardboards are panel products made by reducing wood substance to particles or fiber and reconstituting the fiber into stiff panels 1.2 by 2.4 m (4 by 8 ft) in area or larger. Insulation board is of either interior or water-resistant quality, and is usually manufactured for use where combinations of thermal and sound-insulating properties and stiffness and strength are desired. Hardboard with a density of 50 lb/ft³ or more is used in many applications where a relatively thin, hard, uniform panel material is required. Of great importance in the electrical field are special high-density hardboard products expressly manufactured with high dielectric properties. Medium-density fiberboards have a density between that of insulation board and hardboard.

Particle boards are panel products made by gluing small pieces of wood in a form such as flakes (this product is called waferboard) and shavings into relatively thick, rigid panels. Thermosetting resins are used to provide bonds of either interior or water-resistant quality. Standards ASTM C208 and ANSI A208.1 and PS58 govern minimum qualities of regular insulation board, particle board, and hardboard. The important physical and strength properties of various board products are indicated by Table 4-19.

There are many engineered-wood products now available for structural use. In addition to plywood, which has already been discussed, they include glued-laminated timber, wood I-joists, oriented-strand board (OSB), laminated-veneer lumber (LVL), parallel-strand lumber (PSL), and laminated-strand lumber (LSL). All these products require structural engineering input in their design, manufacture, and end use. There are many advantages in using these products compared with solid wood.

4.5.9 Wood Poles and Crossarms

Douglas-fir (Coast) and Southern pine as a group of four species, loblolly, longleaf, shortleaf, and slash pine, are the most commonly used in the United States to support electric supply and communication lines, cables, and equipment. In the Northeast part of the country, there are still some chestnut and also Northern white cedar poles in service, but these species are no longer available for purchase. Western red cedar, lodgepole and ponderosa pines, and Western larch are used to a limited extent in the Western states. Other species are shown in the ANSI 05.1 Specification size/class tables, but many of those are not provided for orders due to lack of supply or lack of fabricating and treating sources.

4.5.10 Standards for Wood Poles

The ANSI specifications for wood poles serve as a basis for purchasing and use. The ANSI specifications cover fiber stresses, dimensions, defect limitations, and manufacturing requirements. The fiber stresses approved by the ANSI and contained in its Standard 05.1 are as shown in Tables 4-20, 4-21, 4-22, and 4-23. These tables cover all species of poles normally used in communication and electrical power construction.

TABLE 4-19 Strength and Mechanical Properties of Selected Wood-Based Composite Products*

Material	Density, lb/ft	Specific gravity	Modulus of rupture, lb/in ²	Modulus of elasticity (bending), 1,000 lb/in ²	Tensile strength parallel to surface, lb/in ²	Tensile strength perpendicular to surface, lb/in ²	Compression strength parallel to surface, lb/in ²	24-h water absorption		Thickness swelling, 24-h soak, %	Maximum linear expansion, [†] %	Thermal conductivity Btu/(ft ²)(h)(°F) (in thickness)
								% by volume	% by weight			
Fibrous-felted boards:												
1. Structural insulating board	10-26	0.16-0.42	200-800	25-125	200-500	10-25	—	1-10	—	—	0.5	0.27-0.45
2. Hardboard												
a. Tempered	60-80	0.96-1.28	6,000	800-1,000	3,000	130	4,200	—	10-30	9-25	0.4	1.10-1.50
b. Standard	50-80	0.80-1.28	4,500	400-800	2,200	90	1,800	—	15-40	10-30	0.6	0.8-1.40
Particle boards:												
1. High density, grade I-H-2	50-70	0.8-1.12	3,000	350	—	130	—	—	—	—	—	0.4-1.0
2. Medium density, grade I-M-2	37-50	0.6-0.8	2,100	325	—	60	—	—	—	—	—	1.1-1.5
3. Waferboard	37-42	0.6-0.67	2,500	450	—	50	—	—	—	20-25	0.2	
Veneered boards:												
1. Plywood with Douglas fir or southern pine faces, dry use:												
a. Grade stress level S-1	30-37	0.46-0.59	2,000	1,800	1,400	120	1,060					
b. Grade stress level S-2	30-37	0.46-0.59	1,650	1,800	1,200	120	990					
2. Paralam	30-37	0.46-0.59	2,900	2,000	2,400		2,900					

Note: 1 lb/ft = 1.88 kg/m; 1 lb/in² = 6.895 kPa.

*The data presented are general round-figure values, accumulated from numerous sources; for more exact figures on a specific product, individual manufacturers should be consulted or actual tests made. Values are for general laboratory conditions of temperature and relative humidity.

†Expansion resulting from a change in moisture content from equilibrium at 50% relative humidity to equilibrium at 90% relative humidity.

TABLE 4-20 Dimensions of Northern White Cedar and Engelmann Spruce Poles

	Class		1	2	3	4	5	6	7	9	10
	Minimum circumference at top, in		27	25	23	21	19	17	15	15	12
	Length of pole, ft	Ground-line distance from butt,* ft	Minimum circumference at 6 ft from butt, in								
Northern white cedar poles (based on a fiber stress of 4,000 lb/in ²)	20	4	38.0	35.5	33.0	30.5	28.0	26.0	24.0	22.0	17.5
	25	5	42.0	39.5	36.5	34.0	31.5	29.0	27.0	24.0	19.5
	30	5½	45.5	43.0	40.0	37.0	34.5	32.0	29.5	26.0	
	35	6	49.0	46.0	42.5	39.5	37.0	34.0	31.5		
	40	6	51.5	48.5	45.0	42.0	39.0	36.0			
	45	6½	54.5	51.0	47.5	44.0	41.0				
	50	7	57.0	53.5	49.5	46.0	43.0				
	55	7½	59.0	55.5	51.5	48.0	44.5				
	60	8	61.0	57.5	53.5	50.0					
Engelmann spruce poles (based on a fiber stress of 5,600 lb/in ²)	20	4	34.5	32.0	30.0	28.0	25.5	23.5	22.0	19.0	15.0
	25	5	38.0	35.5	33.0	30.5	28.5	26.0	24.5	21.0	16.5
	30	5½	41.0	38.5	35.0	33.0	30.5	28.5	26.5	22.5	
	35	6	43.5	41.0	38.0	35.5	32.5	30.5	28.0		
	40	6	46.0	43.5	40.5	37.5	34.5	32.0			
	45	6½	48.5	45.5	42.5	39.5	36.5				
	50	7	50.5	47.5	44.5	41.0	38.0				
	55	7½	52.5	49.5	46.0	42.5	39.5				
	60	8	54.5	51.0	47.5	44.0					
	65	8½	56.0	52.5	49.0	45.5					
	70	9	57.5	54.0	50.5	47.0					
	75	9½	59.5	55.5	52.0						
	80	10	61.0	57.0	53.5						
	85	10½	62.5	58.5	54.5						
	90	11	63.5	60.0	56.0						
	95	11	65.0	61.0							
	100	11	66.0	62.0							

Notes: Classes and lengths for which circumferences at 6 ft (1.83 m) from the butt are listed in boldface type are the preferred standard sizes. Those shown in light type are included for engineering purposes only.

1 in = 2.54 cm; 1 ft = 0.3048 m; 1 lb/in² = 6.895 kPa.

*The figures in this column are intended for use only when a definition of ground line is necessary in order to apply requirements relating to scars, straightness, etc.

Pole Dimensions. The circumference at “6 ft (1.8 m) from butt” in ANSI Standard 05.1 is based on the following principles:

- The classes from the lowest to the highest were arranged in approximate geometric progression, the increments in breaking load between classes being about 25%.
- The dimensions were specified in terms of circumference in inches at the top and circumference in inches at 6 ft from the butt for poles of the respective classes and lengths, except for three classes having no requirement for butt circumference.
- All poles of the same class and length were to have, when new, approximately equal strength or, in more precise terms, equal moments of resistance at the ground line.
- All poles of different lengths within the same class were of sizes suitable to withstand approximately the same breaking load, on the assumption that the load is applied 0.6 m (2 ft) from the top and that the break (failure) would occur at the ground line.

TABLE 4-21 Western Red Cedar, Ponderosa Pine, and Poles of Other Species

	Class		1	2	3	4	5	6	7	9	10
	Minimum circumference at top, in		27	25	23	21	19	17	15	15	12
	Length of pole, ft	Ground-line distance from butt,* ft	Minimum circumference at 6 ft from butt, in								
Western red cedar and ponderosa pine poles (based on a fiber stress of 6,000 lb/in ²)	20	4	33.5	31.5	29.5	27.0	25.0	23.0	21.5	18.5	15.0
	25	5	37.0	34.5	32.5	30.0	28.0	25.5	24.0	20.5	16.5
	30	5½	40.0	37.5	35.0	32.5	30.0	28.0	26.0	22.0	
	35	6	42.5	40.0	37.5	34.5	32.0	30.0	27.5		
	40	6	45.0	42.5	39.5	36.5	34.0	31.5			
	45	6½	47.5	44.5	41.5	38.5	36.0	33.0			
	50	7	49.5	46.5	43.5	40.0	37.5				
	55	7½	51.5	48.5	45.0	42.0					
	60	8	53.5	50.0	46.5	43.5					
	65	8½	55.0	51.5	48.0	45.0					
	70	9	56.5	53.0	49.5	46.0					
	75	9½	58.0	54.5	51.0						
	80	10	59.5	56.0	52.0						
	85	10½	61.0	57.0	53.5						
	90	11	62.5	58.5	54.5						
	95	11	63.5	59.5							
	100	11	65.0	61.0							
	105	12	66.0	62.0							
	110	12	67.5	63.0							
	115	12	68.5	64.0							
	120	12	69.5	65.0							
	125	12	70.5	66.0							
	Class		1	2	3	4	5	6	7	9	10
	Minimum circumference at top, in		27	25	23	21	19	17	15	15	12
	Length of pole, ft	Ground-line distance from butt,* ft	Minimum circumference at 6 ft from butt, in								
Jack pine, lodgepole pine, red pine, redwood, Sitka spruce, Western fir, and white spruce poles (based on a fiber stress of 6,600 lb/in ²)	20	4	32.5	30.5	28.5	26.5	24.5	22.5	21.0	18.0	14.5
	25	5	36.0	33.5	31.0	29.0	27.0	25.0	23.0	20.0	15.5
	30	5½	39.0	36.5	34.0	31.5	29.0	27.0	25.0	21.0	
	35	6	41.5	38.5	36.0	33.5	31.0	28.5	26.5		
	40	6	44.0	41.0	38.0	35.5	33.0	30.5			
	45	6½	46.0	43.0	40.0	37.0	34.5	32.0			
	50	7	48.0	45.0	42.0	39.0	36.0				
	55	7½	49.5	46.5	43.5	40.5					
	60	8	51.5	48.0	45.0	42.0					
	65	8½	53.0	49.5	46.0	43.0					
	70	9	54.5	51.0	47.5	44.5					
	75	9½	56.0	52.5	49.0						
	80	10	57.5	54.0	50.5						
	85	10½	58.5	55.0	51.5						
	90	11	60.0	56.5	52.5						
	95	11	61.5	57.5							
	100	11	62.5	58.5							
	105	12	63.5	60.0							
	110	12	65.0	61.0							
	115	12	66.0	62.0							
	120	12	67.0	63.0							
	125	12	68.0	64.0							

TABLE 4-22 Alaska Yellow Cedar, Western Hemlock, Douglas Fir, and Southern Pine Poles

	Class		1	2	3	4	5	6	7	9	10
	Minimum circumference at top, in		27	25	23	21	19	17	15	15	12
	Length of pole, ft	Ground-line distance from butt,* ft	Minimum circumference at 6 ft from butt, in								
Alaska yellow cedar and Western hemlock poles (based on a fiber stress of 7,400 lb/in ²)	20	4	31.5	29.5	27.5	25.5	23.5	22.0	20.0	17.5	14.0
	25	5	34.5	32.5	30.0	28.0	26.0	24.0	22.0	19.5	15.0
	30	5½	37.5	35.0	32.5	30.0	28.0	26.0	24.0	20.5	
	35	6	40.0	37.5	35.0	32.0	30.0	27.5	25.5		
	40	6	42.0	39.5	37.0	34.0	31.5	29.0			
	45	6½	44.0	41.5	38.5	36.0	33.0	30.5			
	50	7	46.0	43.0	40.0	37.5	34.5				
	55	7½	47.5	44.5	41.5	39.0					
	60	8	49.5	46.0	43.0	40.0					
	65	8½	51.0	47.5	44.5	41.5					
	70	9	52.5	49.0	46.0	42.5					
	75	9½	54.0	50.5	47.0						
	80	10	55.0	51.5	48.5						
	85	10½	56.5	53.0	49.5						
	Class		1	2	3	4	5	6	7	9	10
	Minimum circumference at top, in		27	25	23	21	19	17	15	15	12
	Length of pole, ft	Ground-line distance from butt,* ft	Minimum circumference at 6 ft from butt, in								
Douglas-fir and Southern pine poles (based on a fiber stress of 8,000 lb/in ²)	20	4	31.0	29.0	27.0	25.0	23.0	21.0	19.5	17.5	14.0
	25	5	33.5	31.5	29.5	27.5	25.5	23.0	21.5	19.5	15.0
	30	5½	36.5	34.0	32.0	29.5	27.5	25.0	23.5	20.5	
	35	6	39.0	36.5	34.0	31.5	29.0	27.0	25.0		
	40	6	41.0	38.5	36.0	33.5	31.0	28.5			
	45	6½	43.0	40.5	37.5	35.0	32.5	30.0			
	50	7	45.0	42.0	39.0	36.5	34.0				
	55	7½	46.5	43.5	40.5	38.0					
	60	8	48.0	45.0	42.0	39.0					
	65	8½	49.5	46.5	43.5	40.5					
	70	9	51.0	48.0	45.0	41.5					
	75	9½	52.5	49.0	46.0						
	80	10	54.0	50.5	47.0						
	85	10½	55.0	51.5	48.0						
	90	11	56.0	53.0	49.0						
	95	11	57.0	54.0							
	100	11	58.5	55.0							
	105	12	59.5	56.0							
	110	12	60.5	57.0							
	115	12	61.5	58.0							
	120	12	62.5	59.0							
	125	12	63.5	59.5							

Notes: Classes and lengths for which circumferences at 6 ft (1.83 cm) from the butt are listed in boldface type are the preferred standard sizes. Those shown in light type are included for engineering purposes only.

1 in = 2.54 cm; 1 ft = 0.3048 m; 1 lb/in² = 6.895 kPa.

*The figures in this column are intended for use only when a definition of ground line is necessary in order to apply requirements relating to scars, straightness, etc.

TABLE 4-23 Western Larch Poles

	Class		1	2	3	4	5	6	7	9	10
	Minimum circumference at top, in		27	25	23	21	19	17	15	15	12
	Length of pole, ft	Ground-line distance from butt,* ft	Minimum circumference at 6 ft from butt, in								
Western larch poles (based on a fiber stress of 8,400 lb/in ²)	90	11	57.5	54.0	50.5						
	95	11	58.5	55.0							
	100	11	60.0	56.0							
	105	12	61.0	57.0							
	110	12	62.0	58.0							
	115	12	63.0	59.0							
	120	12	64.0	60.0							
	125	12	65.0	61.0							
	20	4	30.0	28.5	26.5	24.5	22.5	21.0	19.0	17.0	13.5
	25	5	33.0	31.0	29.0	26.5	24.5	23.0	21.0	18.5	14.5
	30	5½	35.5	33.5	31.0	29.0	26.5	24.5	23.0	19.5	
	35	6	38.0	35.5	33.0	31.0	28.5	26.5	24.5		
	40	6	40.0	37.5	35.0	32.5	30.0	28.0			
	45	6½	42.0	39.5	37.0	34.0	31.5	29.0			
	50	7	44.0	41.0	38.5	35.5	33.0				
	55	7½	45.5	42.5	40.0	37.0					
	60	8	47.0	44.0	41.0	38.5					
	65	8½	48.5	46.0	42.5	39.5					
	70	9	50.0	47.0	44.0	41.0					
	75	9½	51.5	48.0	45.0						
	80	10	52.5	49.5	46.0						
	85	10½	54.0	50.5	47.0						
	90	11	55.0	51.5	48.5						
	95	11	56.5	53.0							
	100	11	57.5	54.0							
	105	12	58.5	55.0							
	110	12	59.5	56.0							
	115	12	60.5	57.0							
	120	12	61.5	58.0							
	125	12	62.5	58.5							

Notes: Classes and lengths for which circumferences at 6 ft (1.83 m), from the butt are listed in boldface type are the preferred standard sizes. Those shown in light type are included for engineering purposes only.

1 in = 2.54 cm; 1 ft = 0.3048 m; 1 lb/in² = 6.895 kPa.

*The figures in this column are intended for use only when a definition of ground line is necessary in order to apply requirements relating to scars, straightness, etc.

The breaking loads referred to in (d) above for the classes for which 6 ft (1.8 m) from butt circumferences are given are as follows: Class 1, 4,500 lb; Class 2, 3,700 lb; Class 3, 3,000 lb; Class 4, 2,400 lb; Class 5, 1,900 lb; Class 6, 1,500 lb; Class 7, 1,200 lb; Class 9, 740 lb; Class 10, 370 lb.

Minimum top circumferences and minimum circumferences at 6 ft (1.8 m) from butt are given in Tables 4-20, 4-21, 4-22, and 4-23.

Length. Poles under 50 ft (15.2 m) in length should not be more than 3 in shorter or 6 in longer than nominal length. Poles 50 ft (15.2 m) or over in length should not be more than 6 in shorter or 12 in longer than nominal length. Length should be measured between the extreme ends of the pole.

Circumference. The minimum circumference at 6 ft (1.8 m) from the butt and at the top, for each length and class of pole, is listed in the tables of dimensions. The circumference at 6 ft (1.8 m) from the butt of poles should be not more than 7 in (17.8 cm) or 20% larger than the specified minimum, whichever is greater. The top dimensional requirement should apply at a point corresponding to the minimum length permitted for the pole.

Classification. The true circumference class should be determined as follows: Measure the circumference at 6 ft (1.8 m) from the butt. This dimension will determine the true class of the pole, provided that its top (measured at the minimum length point) is large enough. Otherwise, the circumference at the top will determine the true class, provided that the circumference at 6 ft (1.8 m) from the butt does not exceed the specified minimum by more than 7 in (17.8 cm) or 20%, whichever is greater. The preceding information relating to the pole standards approved by the ANSI does not constitute the complete standards. For further information, consult the standards, which may be obtained at a nominal charge.

Machine shaving of poles has increased as a practice of producers. Some producers also turn the pole down in the process, thereby obtaining a straighter pole with a specific taper. The machine-processed poles season more rapidly, which is particularly important with species like Southern pine which is susceptible to fungus attack before treatment. Machine shaving makes for easier detection of defects and provides a pole of improved appearance. If poles having normally thin sapwood (such as Western red cedar and larch) are to be full-length when treated with preservative, it is undesirable to reduce the thickness of the sapwood more than necessary to obtain a dressed pole.

Inspection. Poles are inspected prior to treatment for physical defects and decay and after treatment for penetration and retention of preservative and for cleanliness. Inspection is most effective when made at vendors' plants, because defects that may be hidden by preservative are detected and freight is saved on rejects. Commercial inspection agencies are available at most producing locations, and it is normally economical to utilize their services. Quantity users may have their own trained inspectors. *Crossarm inspection* is important because safety of linemen is a consideration in addition to quality of timber. As with poles, inspection should be made before treatment for defects and after treatment for penetration, retention, and cleanliness. Inspection should be done by qualified timber specialists.

Conductivity. Conductivity is of concern to many electric-utility companies. Pole resistance varies greatly with moisture content. Dry wood of all species exhibits high resistance. Surface absorption of rainwater by untreated wood may vary the resistance over a wide range. Full-length treated poles thoroughly dried before treatment generally show only moderate reduction in resistance following a rain. A rough correlation between resistance and moisture will show that 500,000 Ω over a 20-ft length of pole between contacts driven $3\frac{1}{2}$ in deep corresponds to a moisture content of about 25%. Other average points on the curve band are 50,000,000 Ω 15% moisture and 20,000 Ω 40% moisture.

Depth of Pole Setting. The values in the column headed "Ground-line distance from butt" in Tables 4-20 to 4-23 may be accepted as a guide for a satisfactory depth of pole settings in ordinary firm soil. In marshy soil and at unguyed angles in lines, setting depths should be increased 1 to 2 ft (0.3 to 0.6 m). In rock, the indicated settings may be reduced one-half for that part of the pole set in rock. Rock backfill in ordinary earth locations is not considered as set in rock.

Pole Stubbing. Pole stubbing frequently can be employed to effect substantial money savings. An otherwise good pole that is decayed at or below the ground line is fastened securely to a new preservative-treated stub set in the ground alongside it. The major part of the savings resulted from avoidance of transferring wires and equipment.

Salvaging. Poles removed for any reason can frequently be salvaged for future use. Users of large quantities can economically do this. The following operations must be employed: if defective cut off top, butt and retreat, remove old hardware, peel off saprot, reframe, and retreat as required.

Kinds of Timber for Crossarms. Two kinds of timber are in general use for crossarms, Douglas-fir and Southern pine. All pine crossarms are treated with creosote or pentachlorophenol. Crossarms must be treated to achieve long service life.

Most Douglas-fir arms used for communication and power-distribution lines are manufactured from timber selected for the purpose. Dense and close-grain lumber is used. Publication 17 of the West Coast Lumber Inspection Bureau sets forth grading and dressing requirements.

TABLE 4-24 Bending Load and Crushing Strength of Crossarms

Species	Rings per in	Percent			Density (dry)	Max. bending load, lb	Maximum crushing strength lb/sq in
		Summer wood	Sap wood	Moisture			
Douglas fir	20	40	0	11.5	0.48	7,590	7,080
Longleaf pine (50% heart)	18	44	55	13.4	0.54	8,984	5,425
Longleaf pine (75% heart)	19	53	32	13.5	0.63	10,180	8,950
Longleaf pine (100% heart)	16	44	1	12.8	0.63	9,782	8,940
Shortleaf pine	11	46	79	13.3	0.52	9,260	7,300
Shortleaf pine, creosoted	11	49	...	...	...	7,649	5,770
White cedar	12	45	2	14.3	0.36	5,200	4,700

Note: 1 in = 2.54 cm; 1 lb = 0.4536 kg; 1 lb/in² = 6.895 kPa.

There is no grade of Southern pine timber designated as crossarm stock, and crossarm users depend on the limitations set forth in their specifications to obtain a satisfactory quality of product. Pine arms are usually small boxed heart timbers.

Large transmission-line structures are treated round poles and over the past 20 years, laminated towers, arms and braces have more frequently been selected.

Crossarm Specifications. The most widely used specifications for power-line crossarms have been promulgated by ANSI 05.3 as “Solid Sawn-Wood Crossarms and Braces—Specifications and Dimensions” and by the Transmission and Distribution Committee of the Edison Electric Institute. For fir crossarms: Specification TD-90, which combines both dense and close-grain grades; Specification TD-92, Heavy-Duty Douglas-Fir Crossarms; Specification TD-93, Heavy-Duty Douglas-Fir Braces. For pine crossarms: Specification TD-91, Dense Southern Pine Crossarms Preservative Treated. Widely used specifications for communication crossarms are American Telephone and Telegraph Co. Specification AT-7298. Crossarms. Sawn crossarms are treated with preservatives by pressure processes following AWPAs Standard C25 laminated structures must confirm with the standards of AITC (American Institute of Timber Construction).

Strength of Crossarms. The most reliable source of information on the strength comes from tests made under conditions to simulate crossarms in service. Some tests have been made, and others are under consideration. Theoretical considerations, treating a crossarm as a beam, are valuable if those factors which control the actual strength are taken into account. Tests made several years ago on 84 six-pin, 33¼ by 43¼-in by 6-ft communication crossarms, with a uniformly distributed vertical load, gave average results shown in Table 4-24 (*U.S. Forest Service Circ.* 204, by T. R. C. Wilson). The maximum bending load is the total distributed vertical load. The maximum crushing strength is under compression parallel to the grain. Methods of tests are covered by the appropriate ASTM standards.

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